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THE QUICKSILVER DEPOSITS OF THE TERLINGUA REGION, TEXAS.[1]

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ABSTRACT.

Texas is second among quicksilver-producing States because of the Terlingua region, in the Big Bend of the Rio Grande. This region contains Cretaceous strata, largely calcareous, which grade upward into Tertiary volcanics, locally without break. The strata are cut by numerous intrusions, largely alkalic, and are extensively folded and faulted.

Many of the lodes are near the base of the impervious Del Rio clay, some at higher horizons, and a few in intrusive masses. The solutions penetrated only along open passageways, such as major fractures or joints in zones of tension, and, especially at horizons above the Del Rio, in fractures related to fault zones.

The quicksilver is believed to have been brought in by alkali sulphide solutions. Most other constituents that may once have been present in the solutions had been separated earlier. Precipitation resulted largely from mingling with groundwater. The comparatively low temperature and pressure at the shallow levels where groundwater was present aided the precipitation. As the then-existing zone of groundwater circulation has since been partly exposed by erosion, the lodes are necessarily rather close to the present surface. The gangue minerals, particularly the calcite, are believed to have been derived mainly from the sedimentary rocks with some addition of material from deep sources. The relation of the widespread bitumen to genesis is puzzling here, as in many other quicksilver deposits. Weathering is of slight economic importance. Many minerals that resemble supergene products, including the quicksilver chlorides, are thought to have resulted here from original deposition within the zone of vadose water.

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[1] Published by permission of the Director, Geological Survey, United States Department of the Interior.

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FOREWORD.

THE quicksilver deposits of the Terlingua region in the Big Bend of the Rio Grande are of interest both because this small area has long kept Texas second among the quicksilver-producing States and because of the light they throw on problems of the genesis of deposits of this metal in general. The region includes the Terlingua district and the nearby, smaller Mariscal area. Both districts were examined by the writer in 1934, at a time when they were in active operation.

The present paper is a summary of the results of the study made in 1934. A more complete report with detailed maps and descriptions of individual properties is expected to be published in due course by the Geological Survey.

The deposits of Texas are mainly in calcareous rocks. In this respect they resemble those of Mexico but differ from most quicksilver lodes in the United States. Although this difference gives rise to departures in mineralogy and form of the deposits, the fundamental genetic features of all cinnabar lodes are believed to have much in common. In most places deposition has taken place relatively close to the surface and under structural conditions that permitted easy access to particular places and concentration there of large volumes of the solutions. Hypogene cinnabar solu-

tions are so dilute and circulate at such comparatively low pressure and temperature that they have little capacity to force a passage for themselves either by means of mechanical power or chemical replacement. They commonly contain few other heavy metals.

The writer's field work was greatly facilitated by the able assistance rendered him by W. E. Cartwright and C. H. Coldwell and, during parts of the time, by J. A. Connors and H. E. Stocking. The mining men and other residents of the region were without exception hospitable and helpful in every way within their power. A long-established policy of secrecy made the information obtainable at the Chisos mine scanty, but in other respects all possible information and assistance were freely given.

LOCATION.

All of the quicksilver mines in Texas lie within what is sometimes termed the Terlingua region in the Big Bend of the Rio Grande in the western part of the State. This region extends from the Solitario in Brewster County, to where Mariscal Mountain crosses the Rio Grande into Mexico. Although some quicksilver is known in other parts of the Big Bend, none has been mined elsewhere; there are also undeveloped quicksilver prospects in neighboring parts of Mexico. Within the Terlingua region, nearly all of the mines are grouped in the Terlingua district, but there are a few near the northern end of Mariscal Mountain, and some minor prospects in localities outside of either district.

The Terlingua district centers around the settlement of that name, which is about 84 miles from the Southern Pacific Railroad at Alpine and somewhat further from Marathon, the principal shipping point. (Fig. 1.) The district is about 14 miles long in an easterly direction and 4 miles wide. In 1934 it contained about 30 mines and prospects, nearly all of which were then or recently had been in operation.

The Terlingua region contains no other metalliferous deposits of proved value, although gold-bearing lodes and placer deposits have been reported in and near the Chisos Mountains, and a little

prospecting for lead, zinc, gold, and silver has been done in the Solitario. The recorded production from all of these has been trivial and the deposits are not further referred to in the present paper.

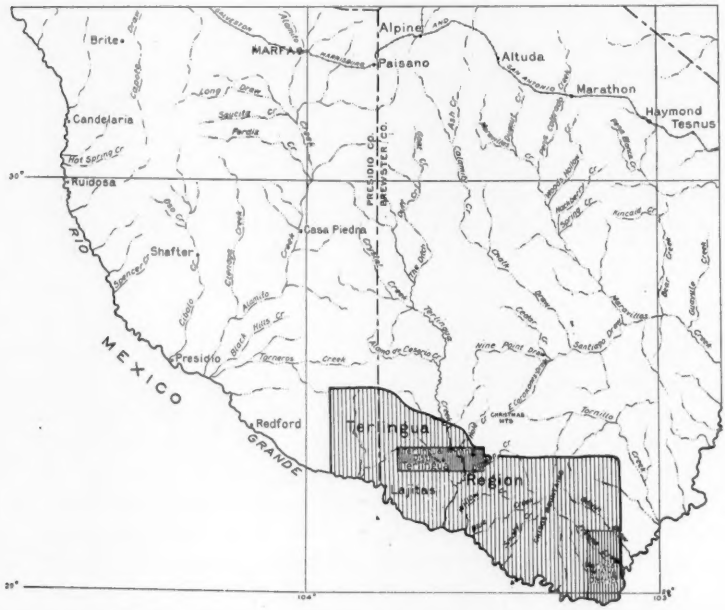

FIG. 1. Map of parts of Brewster and Presidio Counties, Texas, showing the location and extent of the Terlingua and Mariscal mining districts.

HISTORY.

One of the principal trails used by the Indians in travelling to and from Mexico passed through the Terlingua district. They used the red iron oxide that is conspicuous at many of the quicksilver deposits as a pigment but are not known to have used cinnabar for any purpose. Reports of the presence of quicksilver reached white men as early as 1850, but no mining appears to

have been undertaken prior to 1894 and production of substantial amounts of quicksIver did not begin until about 1899 at what is now called the Mariposa mine in the western part of the Terlingua district. Activity at and close to this mine continued until about 1910 and from 17,000 to 30,000 flasks of quicksilver are locally estimated to have been obtained during this period. In 1902 or 1903 the Chisos Mining Company began operations at the present settlement of Terlingua and soon became the principal producer in the district. Cinnabar was discovered near the eastern end of the district in 1902, and since then there has been considerable production from mines at Study Butte and smaller quantities from others in this part of the district. Cinnabar was found at Mariscal Mountain southeast of the Terlingua district, about 1900, and a little mining was done there by Ed. Lindsley.

In the period from 1910 to the outbreak of the World War the Chisos was almost the only mine in operation. The high prices during wartime caused the reopening of most of the properties throughout the Terlingua and Mariscal districts, but nearly all, except the Chisos, were shut down again about 1920. From 1927 to 1936 there was a renewal of activity. Several new organizations entered the district at this time and mined for brief periods. Of these, the group that took over the old, but formerly non-productive, Rainbow mine was the most successful. This mine, which is a short distance west of Terlingua, is reported to be one of the few that remained in production in 1938. Nearly all the other mines in the district had then either shut down or were engaged mainly in development work.

Available information as to the total output of the Terlingua and Mariscal districts is scanty and unsatisfactory. Published data and estimates of yields by local men leads to the conclusion that the total production through 1938 exceeds 150,000 flasks and may be nearly 200,000 flasks. The greater part of this total came from the Chisos mine at Terlingua, which, until recently, has been both the largest and the most steadily active mine in Texas. In total output it probably excels all but three of the Californian mines, and is approached by only four others in that State, even

though quicksilver mining began far earlier in California than in the Terlingua region. Outside of these two States, no quicksilver district in the United States has an output comparable to that of the Chisos mine.

GENERAL GEOLOGY.

Stratified Rocks.—The strata in the Terlingua region range in age from early Paleozoic to Tertiary, but only Cretaceous beds are exposed in the immediate vicinity of the mines. There are a number of intrusive rocks of Tertiary age, some of which are in and near the mines.

The section tabulated below lists the stratigraphic nomenclature that has been adopted for the rocks of the Terlingua region. The names in this table have already been used in or near the region, but the usage here adopted differs in several respects from any proposed for the rocks of the Terlingua region prior to 1934. The object in thus defining the different formations was to obtain definite map units that could be recognized in the field by their lithologic characteristics, and to avoid the use of formation names well-established in other parts of Texas for local units whose equivalence is unproved or doubtful. Most of the formation names here used were proposed by Udden [2] in his pioneer studies in this part of Texas, although more refined mapping has necessitated some modification of his definitions. Udden, in his original work in the Terlingua region, assigned no name to the beds here called Devils River limestone although, in the second report cited above, he proposed that name for essentially similar beds in another area in western Texas. These beds are at present locally called the Georgetown and Edwards limestone. Beds that correspond in age to both of these formations may well be present in the region, but, as no satisfactory distinction between the rocks so designated seems possible, the more inclusive term Devils River limestone has been adopted. The only diagnostic fossils found in

[2] Udden, J. A.: A sketch of the geology of the Chisos County, Brewster County, Texas. Univ. Texas Bull. 93: 21–60, 1907. Report on a geological survey of the lands belonging to the New York and Texas Land Co., Ltd., in the Upper Rio Grande embayment in Texas. Augustana Library Pub. No. 6, p. 56, 1907.

this unit during the present study are regarded by J. B. Reeside as of Edwards age.

STRATIGRAPHIC SECTION, TERLINGUA REGION.

Age and Age equivalents.			Formations.
Tertiary			Chisos volcanics Lava, tuff, minor amounts of conglomerate, and other sediments; thickness, several thousand feet.
Cretaceous	Upper Cretaceous	Navarro	Tornillo clay Variegated sandy clay, partly tuffaceous; 600–1,000 feet.
			Aguja formation Cross-bedded sandstone, argillaceous and calcareous beds and coal; 1,000 feet ±.
		Taylor	
		Austin	Terlingua clay Mainly dark structureless clay, 0–1,000 feet (?).
		Eagle Ford	Boquillas flags Slabby argillaceous and sandy calcareous rocks; 1,000 feet ±.
	Lower Cretaceous	Washita	Buda limestone White limestone with conchoidal fracture, 0–100 feet.
			Del Rio clay Compact dark argillaceous rock, somewhat calcareous, 80–200 feet +.
		Fredericksburg	Devils River limestone Mainly thick-bedded limestone with chert concretions, 1,500 feet.
		Trinity	Early Cretaceous strata Limestone with conglomerate and sandstone below.
Carboniferous		Pennsylvanian	Tesnus formation Mainly sandstone and shale.
Devonian (?)			Caballos novaculite
Ordovician			Maravillas chert with an unnamed green shale
Cambrian			Early Ordovician and Cambrian strata

The distribution of the rock units in the Terlingua region is shown in generalized fashion on Fig. 2. The Paleozoic and early Cretaceous formations are exposed only in the structural dome of the Solitario. This part of Fig. 2 is based on a map furnished by the Texas Bureau of Economic Geology, with minor modifications based on a brief visit by Philip B. King and the writer in 1934. The rest of Fig. 2 is adapted from the geologic map of the region prepared by the writer's party.

The quicksilver mines contain representatives of formations from the Devils River to the Terlingua inclusive, and traces of

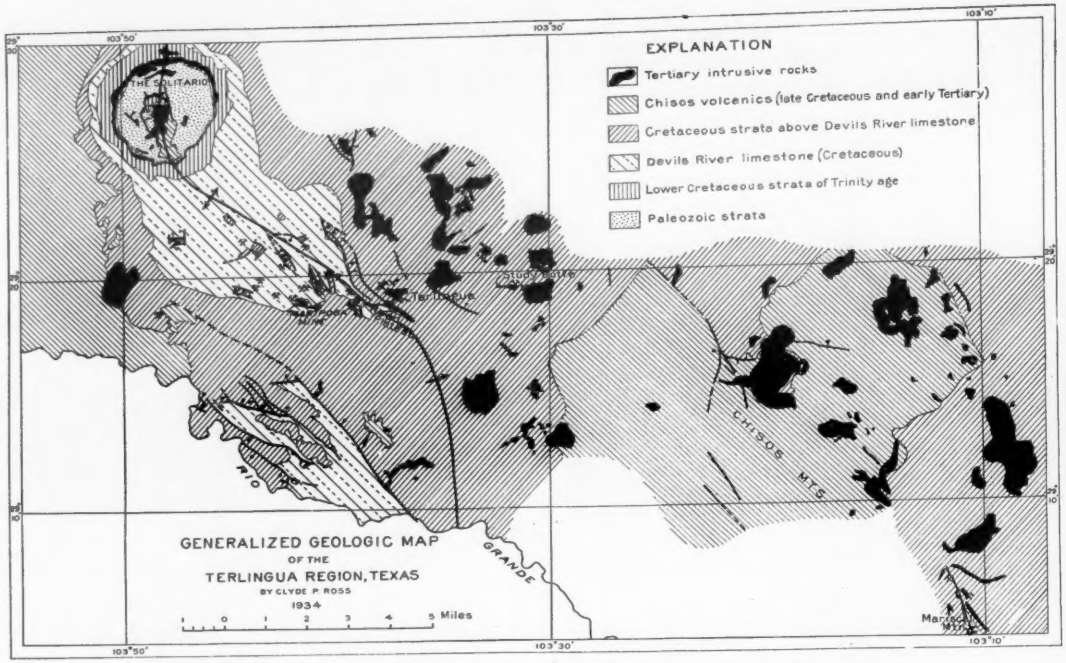

FIG. 2. Generalized geologic map of the Terlingua region, Brewster County, Texas.

cinnabar have been reported from higher horizons. By far the greater number of known ore bodies are close to the contact between the thick-bedded, jointed Devils River limestone and the comparatively impervious Del Rio clay; however, a large share of the output from the Chisos and a few of the other mines has come from higher horizons, especially the Boquillas flags. It is noteworthy that in this region, unlike many others, most of the quicksilver ore is in calcareous rocks.

Igneous Rocks.—In several parts of the region, notably in and near the eastern part of the Terlingua mining district, there are many small intrusive masses, principally irregular sills, plugs, and dikes. Over 13 separate bodies were mapped, but few exceed a mile in diameter of outcrop. Some of the intrusives consist of ferromagnesian rocks akin to basalt, but many, including the larger masses, have the composition of keratophyre, soda trachyte, and similar alkalic rocks. There are also some intrusions of somewhat sodic andesite. Many of the basaltic rocks and some of the others show the effects of albitization and analcitization. The lavas in the Chisos volcanics are similar in composition to the intrusive rocks and the two may be genetically related. Igneous activity began in the Terlingua region late in Cretaceous time but most, if not all, of the lava flows and intrusive rocks there exposed are thought to be of early Tertiary age. In parts of the region no perceptible stratigraphic break exists between the Cretaceous sedimentary rocks and the flows.

Cinnabar lines fractures in intrusive rocks of several different kinds in the Terlingua region; for example, in the Mariposa, Study Butte, and Mariscal mines. At Study Butte, especially, quartz trachyte is the host rock of the principal orebodies. Hence ore deposition was later than the intrusive activity and may be genetically related thereto. As intrusion in this region appears to have taken place rather early in the Tertiary, it is possible that the quicksilver deposits here are older than many of those in California, which are regarded as of Pliocene and later age.

Structure.—The Cretaceous beds in the Terlingua region rest on complexly folded and faulted Paleozoic rock, exposed only in

the Solitario. P. B. King in a note to be included in the official report on this region points out that the structures in the old rocks are completely at variance with those in the Cretaceous beds and are similar to those in Paleozoic rocks, both in the Marathon Basin somewhat farther east in west Texas and in the Ouachita Mountains in Oklahoma and Arkansas.

The Cretaceous strata of the Terlingua region have been broadly flexed with narrow zones of sharp folding on the southwestern flanks of the anticlines. Normal faults of several kinds are plentiful and some reverse faulting has taken place. The Tertiary strata, preserved mainly in synclines, have, on the whole, been less sharply folded than the Cretaceous rocks. The folds trend northwest. The principal folds are the asymmetric, thrust-faulted anticline that makes up Mariscal Mountain, the shallow, faulted syncline that includes the Chisos Mountains, and the compound, faulted, Terlingua anticline.

The Terlingua anticline, which is the largest and most complex of these features, has a total length of about 55 miles, but nearly half of it is in Mexico and was not studied by the writer. This portion of the anticline has been mapped by Cumming.[3] Immediately north of the Rio Grande the anticline is somewhat ill-defined and is broken by faults. In Reed Plateau (Fig. 2) it is well exposed and trends about N. 50° W. Here it is broken by faults on the eastern and flexed on the western flank. Near the northern end of this plateau the anticline, especially its southwestern flank, swings almost due west. It maintains this trend for about 8 miles, then turns about N. 20° W. to its culmination in the structural dome of the Solitario some 10 miles to the north. The southwest flank north of Reed Plateau is sharply bent, locally even slightly overturned. Part of the narrow zone of sharp folding here is shown in Fig. 4. In most of the median portion of the anticline dips are gentle except where locally disturbed by faulting. The northeast flank is poorly defined and irregular. Dips are moderate except in some of the local zones of flexure and

[3] Cumming, Jorge: Reconocimiento geologico-petrolio, de la parte norte del Estado de Coahuila. Mex. Instituto Geologico. Folleto de Divulgacion No. 29, map, 1928.

faulting. Part of the irregularity in the structure here and farther east results from the numerous small intrusions.

The sharp bend in the anticline west of the north end of Reed Plateau is interpreted as the result of a thrust movement. The rocks at this place are markedly bent and contorted (Fig. 4) but have undergone little actual breaking. These effects of deformation suggest that, if thrusting had been sufficient to cause rupture, the rocks in the broad plain south of the Mariposa mine would have been overridden by the older beds, and a tear fault would have been formed close to the present exposed boundary of the Devils River limestone east of the Mariposa mine. Such thrusting must have caused the rock mass immediately west of the plateau to have moved eastward under compression with corresponding tensional stresses in the area to the north, where many of the quicksilver lodes are. The greater ease of passage along fractures in such a zone of tension is thought to account for the localization of the lodes here. The boundary between the compressional and tensional areas corresponds approximately to the contact between the Devils River limestone and overlying beds in this part of this area (Fig. 2).

Faulting is conspicuous around Terlingua. Close to the Rio Grande, in the southwestern part of the area (Fig. 2), there is a complex of faults, mainly of northwest trend. Another set of northwest-trending faults lies within a complex, narrow graben between Terlingua and Reed Plateau. A number of small isolated grabens are scattered along the crest of the main anticline from a point west of Terlingua almost to the Solitario. The longer sides of the grabens are formed by faults of the dominant northwest-trending system but some are terminated or crossed by faults of northeast trend.

Mariscal Mountain, in the southeast corner of the area shown in Fig. 2, is a comparatively sharp, asymmetric anticline. The axis of the anticline trends somewhat west of the north and the dips on the western flank are steep or overturned. The anticline contains minor irregularities and is cut by numerous small reverse and normal faults. A number of small intrusive bodies, mainly sills, cut the strata.

The area between the Terlingua and Mariscal anticlines is occupied by a shallow syncline, complicated by numerous small intrusive masses and several faults. The Chisos Mountains, which lie within this syncline area, were studied in less detail than areas in the vicinity of the quicksilver lodes. The broad synclinal structure of the volcanic beds that constitute these mountains is interrupted in several places by local folds.

Fractures.—As many of the quicksilver lodes lie along or are closely controlled by fractures, or joints, the regional fracture or joint systems of the Terlingua region are of direct economic importance. Detailed observations on fractures were confined to the general vicinity of the mines, but the data there obtained are believed to be applicable, in general, to the region as a whole. Fractures with average trends of N. 65° E. and N. 40° W., especially the former, are conspicuous throughout those parts of the Terlingua region underlain by flat or gently flexed expanses of the Devils River limestone and Boquillas flags. Such fractures are present in the grabens as well as in the unbroken blocks. Where beds of any of the formations are sharply folded, the complexity of the stresses locally developed has generally resulted in obscuring any systematic, persistent fractures that may have existed. So many of the sedimentary rocks younger than the Boquillas flags are poorly indurated that fractures in them are rarely either conspicuous or persistent.

The intrusive rocks have fractures that result in part from stresses related to regional deformation, in part from those set up during cooling of molten rock. Fractures related to cooling are the most closely spaced and commonly the most conspicuous, but in many of the intrusives there are numerous fractures approximately parallel to the major fractures in the Devils River and Boquillas formations and probably of similar origin. Individual fractures of this kind are generally longer than those that resulted from cooling.

Solution Features in Limestone.—The calcareous rocks of the Terlingua region and neighboring parts of Texas contain many caves, sinkholes, and collapse breccias, produced by the solvent

action of ground water. These features are all related to the major fractures in the sedimentary rocks.

Solution cavities that range in size from mere pits to openings several hundred feet long are common. The smaller ones are relatively bulbous and many are largely filled with calcite. The larger ones are for the most part enlargements of individual fractures, most of which belong to the major set of northeast trend. These may or may not show evidence of slight faulting, but in general they do not correspond in trend to the faults that have been mapped. These openings are lined with calcite crystals that project into the unfilled cavity and are commonly corroded. Most of these caves are floored and partly filled with horizontally banded clastic material. Stalactites are exceptional and, where present, are clearly of late origin. As underground exploration has been mainly confined to places where the rocks are mineralized, most of the known caves are in the quicksilver mines. Much of the quicksilver ore fills openings of this character.

Distinct, deep, open sinkholes are rare in the Terlingua region. Only one really good example is known. This measures about 80 by 140 feet at the top, widens downward, and is fully 100 feet deep. Shallow depressions, which probably represent sinkholes now largely filled with debris, are present in several places.

In several places blocks of stratified rock, more or less shattered, are embedded in masses of rock that are stratigraphically much lower. The outlines of the shattered masses are roughly square and the sides are approximately parallel to the major joints in the enclosing rock. The most probable explanation of such masses is that solutions moving along fractures removed material at depth and the beds at higher horizons collapsed into the cavities thus formed. Such collapse breccias are visible in and near mine workings close to Terlingua. It is probable that the brecciated mass of rock that yielded most of the ore below the 600 level in the Chisos mine—and the richest that has yet been found in the mine—is of similar character. Permission to examine this mine was not accorded to the present writer, but Ransome [4] states that

[4] Ransome, F. L.: Quicksilver in 1917. In Mineral Resources of the United States, 1917, p. 1, p. 422, 1919.

this mass forms a single chimney from 75 to 100 feet in diameter, explored for more than 150 feet vertically. It is composed largely of shattered Buda limestone enclosed mainly in Del Rio clay.

The abundance of calcite crystals associated with cinnabar and the paucity of stalactites distinguish many of the caves of the Terlingua region; however, in other respects these caves are so similar to those in neighboring parts of Texas and in other limestone regions that they are believed to have had a similar origin, independent of quicksilver mineralization. It is generally agreed that caverns in limestone are formed by downward moving surface water, aided by carbon dioxide that dissolves and mechanically corrades the limestone.[5] The best-known examples are in more humid regions than Terlingua, but solution features of this sort are sufficiently plentiful in neighboring parts of Texas and in New Mexico to show that the aridity of these regions is insufficient to prohibit the process. Once an opening sufficient to permit ready passage of a stream of water is established, enlargement of the opening by corrasion, as in surface streams, becomes effective.

Some features, such as the open sinkholes in the present topography, must be of recent origin and have resulted from processes that are still active. The openings that are partly or wholly filled either with calcite or with collapsed rock from relatively high horizons must have been formed some time ago. Those that contain quicksilver deposits must have been in existence early in Tertiary time. There is reason to think [6] that the climate of that time may have been mild, equable, and more humid than at the present time. The Tertiary fossils on which this conclusion is mainly based are not present within the Terlingua region, but the abundant fossil wood in the Aguja formation, high in the local Cretaceous section, is in accord with the concept. Probably climatic conditions immediately prior to quicksilver mineralization were more favorable to solution by ground water than those of the present day. The more abundant vegetation would tend to result in a

[5] Davis, W. M.: Origin of limestone caverns. G. S. A. Bull. 41: 486, 1930.

[6] Brooks, C. E. P.: The evolution of climate, pp. 42–45. London, 1922. Berry, E. W.: Revision of the lower Eocene Wilcox flora of the southeastern States. U. S. Geol. Surv. Prof. Pap. 156: 33–40, 1930.

higher content of carbon dioxide in the ground water, but the difference in climate does not appear to have been so great as to have produced an excessively shallow water table.

The processes by means of which solution cavities in limestone are formed are still under discussion.[7] The data now at hand appear to favor the concept that most of the excavation of caverns in limestone regions takes place above the water table, although some excavation may also occur below. Obviously excavation below the zone of saturation could be effected, if at all, only through the agency of ascending juvenile water that contained free carbon dioxide or other suitable solvent. As the solutions that brought in the quicksilver are believed to have been strongly alkaline, they were unsuited to dissolve limestone. The incomplete data available indicate that at present the upper limit of ground water in the Terlingua region is probably everywhere less than 1,000 feet below the surface. Under the somewhat more humid climatic conditions that probably existed at the time of ore deposition, ground water was doubtless even closer to the surface, especially if any part of the Chisos volcanics mantled the area at that time. As erosion has been dominant since the close of Chisos volcanism, it follows that those quicksilver ore shoots that constitute cavern fillings or are closely associated with such fillings must lie for the most part at depths of less than 1,000 feet below the present surface. Most known fillings of this kind are less than 300 feet, and many are less than 50 feet, below the surface.

Although the openings in which ore shoots of this sort were formed appear to have been made at depths above those at which the rocks were saturated with ground water, the filling of these openings doubtless took place below the top of the ground water or sufficiently close to that level so that the cavities were at times completely filled with water. The openings, with their coarse, geode-like linings, belong to the kind commonly called "crystal caves." Davis and Swinnerton[8] agree in regarding the crystal

[7] Davis, W. M.: The origin of limestone caverns. G. S. A. Bull. 41: 475–628, 1930. Swinnerton, A. C.: Origin of limestone caverns. G. S. A. Bull. 43: 663–694, 1932.

[8] Davis, W. M.: *op. cit.*, pp. 615–623. Swinnerton, A. C.: *op cit.*, pp. 680–682.

lining as the result of deposition while the cave was full of water; on the other hand, the abundant evidence of circulation of water afforded by the irregular banding in most of the calcite fillings, and by the clastic bands locally associated with them (Fig. 3),

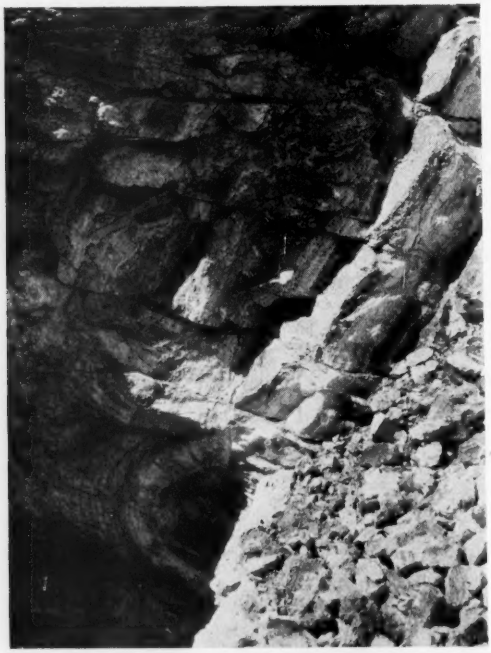

FIG. 3. A calcite lode exposed in a prospect pit near the western end of the Terlingua district. Shows the irregular banding of such fillings of limestone cavities. (Photo by Frank Duncan.)

shows that deposition did not take place under the nearly stagnant conditions usually assumed to exist deep within the zone of saturation. The probability is that filling took place at a time when the openings were near the top of the zone of saturation, in what Meinzer [9] calls the belt of fluctuation, within which the position

[9] Meinzer, O. E.: Outline of ground-water hydrology. U. S. Geol. Surv. W. S. P. 494: 35–36, 1923.

of the water table shifts in response to weather variations and related factors. The rise in ground-water level that brought the openings within this belt may well have been related to the raising of the general level of the country by deposition of the Chisos volcanics. The eruptions are believed to have been among the products of the magmatic period in which the lodes originated. The volcanic beds, therefore, were in place at the time the caves were filled, but cave solution doubtless began before volcanism started.

QUICKSILVER DEPOSITS.

Classes of Lodes and their Distribution.

The quicksilver lodes of the Terlingua region may be divided into three closely related classes: (1) deposits localized along the contact between the Del Rio clay and the Devils River limestone; (2) deposits associated with faults and other openings in strata above the Del Rio clay; (3) deposits in and close to igneous rocks. The resemblances of all the deposits to one another are such as to indicate that the characteristic features on which such a subdivision is based result more from the details of local environment than from fundamental differences in genesis. Such differences in mineral composition as exist seem of slight significance.

The deposits along the contact between the Del Rio clay and the Devils River limestone are much the most abundant. They include nearly all the lodes west of Reed Plateau where the deposits are most numerous and closely spaced. The principal deposits in the Rainbow mine and at least part of the ore in the deeper workings of the Chisos mine, both close to Terlingua, are also included. In most of the other mines in the region this stratigraphic horizon has not yet been explored sufficiently to determine whether it contains any deposits. In the Mariscal district they are not known, possibly in part because development at depth is meager but also because the Del Rio clay is absent or most inconspicuous throughout this district. Evidently in general the massive Devils River limestone with its well-developed fracture system and associated solution cavities provided especially favorable conditions

for the introduction of the solutions and, where present, the Del Rio clay above it constituted an effective means of trapping them.

The known lodes in sedimentary rocks at horizons above the Del Rio clay are few, but they include the deposits in the upper parts of the Chisos and other mines close to Terlingua and those in the Mariscal mine. The Study Butte mine is almost the only one in which deposits in intrusive rock have been extensively mined. Cinnabar, however, has been noted in igneous rock in several places in both districts.

It is noteworthy that the comparatively small number of known lodes of classes 2 and 3 include three of the principal mines, the Chisos, Study Butte, and Mariscal. This scarcity may conceivably be accounted for in part by the fact that deposits of both classes are relatively inconspicuous at the outcrop. They are accompanied by much less red stain in the host rock than those near the base of the Del Rio clay. Another and possibly more potent factor is that most of the known ore deposits at horizons above the Del Rio clay are in the neighborhood of faults that may well have been effective in permitting solutions to pass upward instead of being sealed off by the clay.

Mineralogy.

The principal metallic mineral in nearly all the quicksilver lodes is cinnabar. Native quicksilver, chlorides, and other quicksilver compounds are sufficiently abundant in some places to be of economic importance, but none of them is as widespread or forms such large masses as the cinnabar. Pyrite is widespread, but nowhere abundant. It locally forms nodules in the argillaceous rocks and may, in fact, have crystallized prior to quicksilver mineralization. Oxides of iron are plentiful, especially in the so-called "jaboncillo" of the deposits close to the base of the Del Rio clay. Calcite is the principal introduced gangue mineral in most of the ore. Asphaltic material impregnates much of the calcite and is locally present in discrete masses in and near ore bodies. The host rock, especially in deposits close to the base of the Del Rio clay, is kaolinized and somewhat silicified. Minor

constituents of the mineralized material include aragonite, barite, fluorspar, dolomite, gypsum, manganese oxides, analcite, jarosite, nontronite, and chalcedony. Hill [10] also mentions the presence of "mixtures containing small quantities of arsenic, antimony, and perhaps selenium."

Most of the minerals referred to above are believed to be products of hypogene mineralization, rather than of later supergene alteration. In the Terlingua region, as indicated on a later page the mineralization is believed to have taken place originally at such shallow depths and in such intimate relation to ground water that some resemblance between its products and those commonly ascribed to weathering is to be expected. Under such conditions the minerals originally formed are, for the most part, stable in the zone of weathering, and differences between that and the underlying zone are of little economic significance.

Character of the Lodes.

Lodes near the Base of the Del Rio Clay.—The deposits of economic interest near the base of the Del Rio clay are in general confined to a zone less than 100 feet thick on both sides of the contact, although in a few places ore has been mined more than 300 feet below the contact. Clay minerals of hydrothermal origin have widely converted the rocks, especially the basal beds of the Del Rio into a material locally termed "jaboncillo" because of its soapy feel. The jaboncillo is more or less thoroughly reddened by bands of hematite crystals diffused through it. In many places both hematite and cinnabar are intimately associated within the bands, but the hematite is far more widespread. Fig. 5 illustrates characteristic cinnabar ore in jaboncillo. Most of the cinnabar is confined to rather sharply defined shoots from 1 to 10 feet or more wide, which in places have been followed for a few hundred feet along the strike and a few score feet in depth. These roughly lenticular shoots extend downward into the Devils River limestone and the larger and more persistent bodies lie along open

[10] Hill, B. F.: The Terlingua quicksilver deposits, Brewster County, Texas. Univ. Texas Min. Surv. Bull. 4: 29, 1902.

FIG. 4. View eastward from the hills south of the Mariposa mine. Shows the border of the Terlingua anticline in the segment of westward trend; Devils River limestone forms the hills on the left; Del Rio clay underlies the trough; Buda limestone forms the hogback near the center, and the Boquillas flags are on the right. (Photo by Frank Duncan.)

FIG. 5. Diffusion bands in "Jaboncillo" from the 50 foot level, Mariposa mine. The dark bands are hematite; the bright specks are cinnabar.

fractures that are almost perpendicular to the horizontal or gently inclined limestone beds, with cinnabar-bearing material extending from the fractures into the bedding planes at many places. As cinnabar, locally with calcite, has crystallized along fractures of the systems referred to above as well as along bedding planes and random openings, and as it also has been locally diffused through the rock, especially in and close to crushed material, the ore bodies are highly irregular in detail. In most places, however, the control exercised by the major fractures is clearly evident.

Where crystalline calcite is conspicuous it constitutes linings and fillings of pre-existing solution openings that range in size from mere cracks to single caverns or groups of connected smaller openings that extend scores or even hundreds of feet. Such openings are partly or completely filled by successive bands of calcite crystals, crystalline aggregates, and fragments of limestone. The cinnabar commonly lines spaces between crystal faces and other openings, but locally is reported to be enclosed in calcite crystals. Some of the larger caverns are floored and partly filled with clayey silt, and locally angular rubble, cemented with calcium carbonate. Most of the caverns contain no stalactites, and the few stalactites seen were small and inconspicuous.

Lodes in Strata above the Del Rio Clay.—Most lodes above the Del Rio clay are in the Boquillas flags, but some ore has been found in the underlying Buda limestone. No ore has been mined from sedimentary rocks stratigraphically above the Boquillas flags. The Chisos mine is the only one in which ore shoots in these upper formations have been extensively mined, but, as this mine could not be entered during the present study, details are lacking. Many of the shoots in the Boquillas flags follow steep fractures similar in character and trend to those in the Devils River limestone referred to above. In these the cinnabar occurs in narrow seams filling cracks and scattered through brecciated rock. In many places the cinnabar is the only visible introduced vein mineral. Coarse-grained calcite appears to be less plentiful than it is at lower horizons. Large open caverns have not been reported in any of the rocks above the Devils River limestone. Some of the

cinnabar near Terlingua is on or close to faults related to the graben just west of the town. The extensive fracturing there may be one of the reasons why quicksilver solutions were able to penetrate above the Del Rio clay in sufficient quantity to produce ore deposits. In several places in the general vicinity of Terlingua there are collapse breccias in the Boquillas and other formations, and some of these breccias contain cinnabar. At a mine called the Two-forty-eight nearly three miles east of Terlingua there is an extensive shatter zone impregnated with large quantities of asphalt, thickly studded with analcite. This is probably a collapse breccia. The ore so far mined here, however, has come mainly from deposits related to major fractures in the comparatively unbroken flags.

In the old Mariscal mine, the principal property on Mariscal Mountain, most of the ore shoots lie along a zone of thrust faulting close to the crest of an asymmetric anticline in the Boquillas flags. Altered andesitic sills lie on the hanging-wall side of the thrust zone. Most of the cinnabar lines fractures in the flags just below the sills. In several places on and near Mariscal Mountain, such as the Slaughter property, there are calcite-lined fractures in the flags similar in trend and character to many of those near Terlingua, and some cinnabar has been obtained from them.

Lodes in Igneous Rock.—Cinnabar has been recognized in igneous rock in at least five localities in the Terlingua district, but the Study Butte mine is the only one of known economic importance. Here the cinnabar lines fractures in a wedge-shaped mass of intrusive quartz trachyte.[11] The sedimentary rock beneath is also reported to be locally mineralized.

Lode Systems.

By far the greater part of the quicksilver lodes in sedimentary rocks lie along or are closely associated with fractures of the N. 65° E. system rather than with the faults that are so numerous. Even near Terlingua where the lodes are in part controlled by fissures related to fault zones of northwesterly trend, lodes of the

[11] Ross, C. P.: A spenolith in the Terlingua district, Texas. Trans. Am. Geophys. Union, 1937, Part 1: 255–258.

N. 65° E. trend are among the most productive, especially in the Rainbow mine. On and near Mariscal Mountain the principal known ore shoots are associated with reverse faulting that trends northwest, but several of the prospects are on fractures of the N. 65° E. set. Throughout the region, where mineralized fractures of northeasterly trend cross those of northwesterly trend the effects of mineralization spread into the northwesterly fractures but rarely persist far along them. The fractures of both sets, whether or not mineralized, rarely have much displacement. They do, however, show sufficient brecciation and slicken-siding in places to record minor adjustment. In areas of maximum mineralization the effects of intensified local stresses are recorded by such close spacing of the fractures as to give the limestone a sheeted appearance.

In that part of the intrusive mass at Study Butte that conforms closely to bedding of the enclosing sedimentary rocks most of the stopes are on mineralized fractures of approximately N. 65° E. trend. This is the most productive part of the Study Butte mine. In the southeastern part, where the intrusive mass cuts across the beds, the fractures in the igneous rock, and therefore the ore bodies, are more irregular and discontinuous.

The strong preference shown by the mineralizing solutions for fractures of northeast trend must mean that these fractures provided easier passage than other openings in the rocks. They are transverse to the principal axes of folding and may well have tended to gap open while fractures parallel to the axes of folding were kept tightly closed. Faults were sealed to some degree by gouge and their sides were pressed close together by the very forces that produced the faulting. It has already been pointed out that the part of the region that contains the most numerous ore bodies is in a structural situation that would tend to bring the fractures of northeasterly trend under tension.

Genesis.

The Solutions.—The quicksilver deposits of the Terlingua region were presumably formed late in the period of magmatic activity that produced the Chisos volcanics and the numerous in-

trusives that dot the region. They are thus older than the similar deposits of California, which are believed to be of Pliocene and later age. The quicksilver-bearing fluids are thought to have come from some source so deep that most of the constituents that may originally have been present had already been dropped. The fact that so many of the lodes are in parts of the region comparatively free from outcrops of igneous rock supports this idea, in that it shows that there was no direct relation between the solutions and any of the igneous masses now exposed.

From the character and composition of the deposits and from analogy with laboratory data [12] it appears probable that the quicksilver was carried in hot solutions containing alkali sulphides (especially sodium sulphide), and possibly free alkali in addition. The solutions were dilute and, if they ever contained other heavy metals, most of these had been dropped before the solutions reached the shallow depths at which precipitation took place.

The mineralizing solutions were not under great pressure. They entered cavities that had either already been opened by solution or tension or cracks that could be opened sufficiently by slight pressure. Even in thoroughly shattered ground the closely spaced coatings of cinnabar are commonly very thin and the rock fragments have not been appreciably moved. The ore-forming solutions, therefore, were very dilute and under very slight pressure.

In chemical reactivity likewise the solutions were not powerful. At early stages certain of the rocks were altered, but the products of alteration may record little more than a rearrangement of constituents already present. Clay minerals and red iron oxide are conspicuous in the " jaboncillo " near the base of the Del Rio clay and this material has, locally at least, been somewhat silicified. Chemical and petrographic studies show that, whereas the jaboncillo is strikingly different in appearance from the unaltered rock, the principal changes consist in removal of the carbonate, oxida-

[12] Christy, S. B.: On the genesis of cinnabar deposits. Amer. Jour. Sci., 3rd Series, 17: 453–463, 1879. Becker, G. F.: Geology of the quicksilver deposits of the Pacific slope. U. S. Geol. Surv. Mon. 13: 419–457, 1888. Allen, E. T., and Crenshaw, J. L.: The sulphides of zinc, cadmium and mercury; the crystalline forms and genetic relations. Amer. Jour. Sci., 4th Series, 34: 367–383, 1912. Schuette, C. N.: Occurrence of quicksilver orebodies. A. I. M. E. Tech. Pub. 335: 8–9, 1930.

tion of the iron, and conversion of beidellite-like material into a clay of the kaolin type with some addition of the kaolin mineral and of quartz. The calcite that is the principal constituent of the larger fillings is believed to have been derived mainly from the ground water that obtained it from the calcareous sedimentary rocks that are everywhere abundant. This mineral, however, is distinguished from the rare stalactites of post-mineral origin by a content of maganese oxide, doubtless derived from solutions of magmatic origin. Where calcite lodes, with or without cinnabar, cut formations higher than the Del Rio clay, their wall rocks rarely are visibly altered. The igneous rocks locally associated with the lodes have feldspars clouded with alteration products and ferromagnesian minerals more or less thoroughly altered. The cinnabar itself, in lodes of all kinds throughout the region, was formed mainly by crystallization in open spaces and only to a subordinate extent by chemical replacement.

The fact that the lodes contain few constituents other than those present in the host rocks is in accord with the concept that the cinnabar was deposited from alkali sulphide solutions that no longer contained many other components. As the content of sodium and potassium was not greatly changed by mineralization, it appears that these constituents remained in solution when the cinnabar was precipitated. The igneous rocks of the region show abundant evidence of having been attacked by solutions rich in alkalies (particularly sodium) at late stages in their development.[18] It is conceivable that the alkalies in solutions that had deposited their load of quicksilver sulphide and associated minerals at somewhat greater depths contributed to the alteration in the igneous rocks, most of which as now exposed are at higher horizons than the lodes. This suggestion is strengthened by the presence of abundant analcite with asphalt in a breccia in Boquillas flags in a quicksilver mine near Terlingua.

The lodes of the Terlingua district are distinguished from most quicksilver deposits in the United States by the local abundance of terlinguaite (Hg_2ClO) and a related group of unusual quick-

[18] Stocking, H. E.: The process of analcitization in the Terlingua, Texas, region. Dissertation, Johns Hopkins Univ., 1936.

silver minerals. These minerals are rarely in sufficient abundance to be recognized, but chemical work by J. J. Fahey in connection with studies by the writer, suggests that mercury chlorides in small amount may be more widespread than is commonly supposed. The minerals of this group have been thought to be of supergene origin,[14] but their relations to other minerals are so similar to those of the cinnabar that such an origin seems improbable; furthermore, two of the minerals in the group are dimorphic and are believed to have originally crystallized at temperatures well above the boiling point of water. These are kleinite[15] (hydrous-quicksilver ammonium chlorosulphate) and mosesite[16] (a quicksilver-ammonium compound containing chlorine, sulphur dioxide, and water). The small quantities of minerals of this group seen during the present investigation are along fractures in exceptionally silicified limestone not in the calcite filling of solution cavities. This may explain the presence of minerals with such high crystallization temperatures. Such elevated temperatures were doubtless not attained in the caves where the mineralizing solutions mingled with abundant, comparatively cool ground water. They are much less likely to have been formed under conditions of weathering.

The calcite was formed earlier than most of the cinnabar, and most of it contains bituminous material. In many places the successive bands of calcite are emphasized by differences in color that express differences in the amount of bituminous matter present. The cinnabar that coats crystal faces and interstices, therefore, cannot have been at extremely high temperature when deposited. Certainly, temperatures high enough for introduction of the components of cinnabar in gaseous form would have affected the bitumen. This is among the reasons for doubting the belief of some quicksilver miners that cinnabar forms by sublimation.

The role played by bituminous matter in the formation of quicksilver deposits in general constitutes a puzzling problem. Such

[14] Broderick, T. M.: Some experiments bearing on the secondary enrichment of mercury deposits. Econ. Geol., 11: 645–651, 1916.

[15] Hillebrand, W. F., and Schaller, W. T.: The mercury minerals from Terlingua, Texas. U. S. Geol. Surv. Bull. 405: 18–47, 1909.

[16] Canfield, F. A., Hillebrand, W. F., and Schaller, W. T.: Mosesite, a new mineral from Terlingua, Texas. Amer. Jour. Sci., 4th series, 30: 202–208, 1910.

material is present in so many of the quicksilver deposits throughout the world under such a variety of geologic conditions [17] that its presence cannot be regarded as merely fortuitous. It is commonly assumed [18] that the hydrocarbons are derived from neighboring sedimentary rocks and are introduced into the lodes through the agency of heat and circulating solutions at the time of mineralization. Such a process may be adequate or partially adequate to account for the bitumen in some lodes. As a general explanation, it is unsatisfactory. It is just as much a constituent of the lodes as the cinnabar or the calcite. In the Terlingua region bituminous material is perceptible only within the lodes and is almost everywhere present in them irrespective of the character or stratigraphic position of the wall rocks. In the Two-forty-eight mine, where it is most abundant, it constitutes asphalt masses thickly studded with analcite crystals.

Precipitation.—As the limestone of the Terlingua region shows the effects of extensive pre-mineral solution, it is evident that the ground water present at the time of mineralization was a weakly alkaline calcium bicarbonate water. Mingling of such a water with lesser quantities of an ascending alkaline sulphide solution would result in precipitation of such minerals as now constitute the lodes. The mixture of the two waters would be sufficiently cooler and less alkaline than the ascending solution to cause precipitation of mercuric sulphide. Likewise it would be warmer and sufficiently more alkaline than the ground water to cause precipitation of some of the dissolved calcium carbonate. All the other constituents of the lodes, with the possible exception of the bitumen, were either already present in the rocks or were such as would be commonly found in hot spring waters. The bituminous matter may perhaps have had its original source in sedimentary rock, but tests indicate that it did not come from those close to the principal lodes.

[17] Halse, Edward: Mercury ores. Imperial Institute Monographs on mineral resources with special reference to the British Empire, pp. 22–91, 1923.

[18] Schuette, C. N.: Occurrence of quicksilver ore bodies. A. I. M. E. Tech. Pub. 335: 11–12, 1930.

Recent Modifications.—The hematite originally formed has locally been hydrated by subsequent weathering, and at least parts of the alunite and jarosite exposed in a few places were presumably formed after erosion had brought the lodes closer to the surface. There may perhaps have been slight solution of cinnabar and redeposition of the quicksilver in some form during weathering. None of these late changes appear to be of much economic importance.

Mechanical redistribution of quicksilver-bearing material by streams flowing in open underground passageways subsequent to ore deposition is possible. In a few of the mines the rubble and cave silt that partly fill caves constitute much of the ore. In one mine bones of animals of Pliocene or Pleistocene age have been found in such material.[19] Such features as these led Lonsdale [20] to suggest that the ore in this mine is a filling of solution openings by debris transported by surface storm waters. However, the rubble can be more satisfactorily accounted for as the residue of insoluble and incompletely attacked, broken material resulting from solution by ground water. Locally it is sufficiently sorted to show that it has been transported to some extent by running water, but this could have been easily accomplished by underground streams. Much of the cinnabar in this mine, as in others, has clearly crystallized from solution and is closely associated with unbroken bands of crystalline manganiferous calcite and clay minerals. The animal bones show that solution cavities were open to the surface as early as the end of the Tertiary but any redistribution of the cinnabar that may have resulted is not likely to have been of economic significance.

U. S. GEOLOGICAL SURVEY,
Oct. 1, 1940.

[19] Turner, H. W.: The Terlingua quicksilver deposits. ECON. GEOL., 1: 275, 1906. Lonsdale, J. T.: An underground cinnabar deposit. ECON. GEOL., 24: 629, 1929.

[20] Lonsdale, J. T.: *op. cit.*, pp. 630–631.

HOST–ROCK INFLATION BY VEINS AND DIKES AT GRASS VALLEY, CALIFORNIA.*

ROLLIN FARMIN.

ABSTRACT.

Structural deformation of the rocks of the western Sierra Nevada has developed zones of faulting and of minor partings that are only slightly dilatant, appropriate in deep-seated environment. Gold-quartz veins and dikes of igneous rocks contain inclusion breccias and occupy partings of highly dilatant character—features that may result from the inflation of deep-seated rocks by an injected fluid but would only be associated with near-surface fault fissures. The folding of inter-vein and inter-dike wall rock during inflation of the partings is discordant with an open-fissure environment. Most of the structures found in the gold-quartz veins are likewise found in igneous dikes of comparable size—parallel mechanisms of emplacement are indicated.

INTRODUCTION.

THE gold-quartz veins of Grass Valley, Alleghany, the Mother Lode and other districts of the western Sierra Nevada of California comprise a family characterized by similar mineralogy, textures, structures and geologic relation to the Sierra Nevada batholith. Visiting geologists have studied and ably described these veins, especially in respect to the mineralogy and textures. Geologists resident at the mines gratefully draw on this fund of information but are concerned principally with the megascopic structural features that usually govern the distribution of veins and dikes. These structures unfold piecemeal during the progress of excavation and are never satisfactorily exposed for study by visitors.

Many studies of ores necessarily can be preceded by only short periods of field work at the mines and thus are focused on details of paragenesis of the minerals rather than on broader geologic

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phases. As a result, the quartz veins rarely are appraised as geologic units, now seen after they have survived a full geologic history, but rather are viewed as accumulations from a chemical activity that culminated with the arrival of an inevitably-tardy gold. The field of interpretation of ore genesis seems to have been left largely to the students of ore textures and geochemistry; geologists at the mines are vitally concerned, however, because any philosophy for directing mine development must be based on a theory of ore genesis. Hypotheses of ore genesis should account first for the broad geologic relations, second for the intimate, megascopic relations and only then, after these major problems are solved, for the complex, microscopic detail that becomes increasingly involved as microscopes are improved. This paper directs attention to certain megascopic structures in veins and dikes that appear significant as indicators of the mechanism of their emplacement.

The Problem.—Most of the dikes and the gold-quartz veins along the Sierra Nevada belt occupy dilatant partings in the encasing rocks; the problem is to determine the mechanism of their emplacement. Many geologists now picture vein emplacement as an accretion of crystalline material, precipitating from dilute, magmatic waters that circulate in open spaces developed during fault movements [1] by a progressive bridging of the hanging wall block across irregularities along the footwall block. Although the present writer concurs in the statement that the gold-quartz veins and a variety of dikes commonly occupy the dilatant zones resulting from fault movements, he disagrees with the conclusion that the veins grow by accretion in a succession of partly-open fissures through precipitation from quietly circulating, magmatic waters.

Basis Of Field Work.—Most of the gold-quartz veins here discussed have been observed by the writer at the Grass Valley properties of the Idaho Maryland Mines Corporation, where during his seven years of residence the central operation involved

[1] A recent summary of the mechanics of fault bridging and a bibliography of earlier work is given by Newhouse, W. H.: Openings due to movement along a curved or irregular fault plane. ECON. GEOL., 35: 445–464, 1940.

driving of 45 miles of new headings, excavating 60 acres of stopes and production of about half a million ounces of gold.

Acknowledgments.—Grateful acknowledgment is here accorded to Messrs. Errol MacBoyle and Albert Crase of the Idaho Maryland Mines Corporation for executive and managerial permission to publish the results of work made possible by them. Acknowledgment is also due to colleagues of the mine staff, whose observations and discussions of the veins have been most helpful. A critical review of the manuscript and field evidence by Dr. Earl Ingerson has been stimulating to the writer and has clarified the issue.

DILATANT DEFORMATION IN ROCKS.

The stresses now present in rocks are rarely determined by geologists; whatever stresses preceded geologic faulting can only be a subject for conjecture. Therefore, we are concerned more with geologic strains than stresses so the following discussion of rock deformation throws emphasis on result rather than on cause.

For the purposes of this paper the *movements* along rock partings are defined as follows:

(1) *Shear* is perfectly parallel, opposite gliding along the plane of parting.

(2) *Tension* is perfectly rectangular opening from the plane of parting.

The *Relative Dilation* involved in a movement is the ratio *Tension/Shear,* and it expresses the degree to which a movement opens the parting surfaces. If the movement brecciates the rock, the ratio of specific gravities of solid to broken rock is another measure of the dilation involved.

From the fact that all rocks are somewhat elastic or cohesive, it follows that stresses in them theoretically must be somewhat torsional and that rocks never part in perfect shear or perfect tension. Geologic movements range in type between *slipping,* which closely approaches perfect shear, to splitting, which closely approaches perfect tension. At one extreme, the slips along the smooth, parallel partings of fracture cleavage in slate are only slightly

dilatant; at the other extreme, the ragged cracks which open in splitting mine pillars are highly dilatant. Partings of intermediate type are characterized by their relative dilatancy, which, for example, may amount to 50 per cent in the diagonal opening of a fissure. When a certain dry rock is pulverized for fire assay it is found to dilate 110 per cent through the development of voids; the geologic gouges, however, are found to be only 8–15 per cent dilatant when freshly exposed at a depth of 2000 feet.

Fractures developed along unsupported rock surfaces invariably are highly dilatant, as may be seen in failing mine pillars [2] and in the rocks crushed in testing laboratories. Mine pillars fail by splitting—the common use of the term "sheared" seems inappropriate.

At depth, as restraining support is increased, rocks fail with progressively less dilation, characterized by the following series of structures: open fissures, loose breccia, sandy breccia, fault gouge, "fluccan" (the scaly, intimately sliced rock shavings of the shear zones), drag folds, cross-sheeting, augen and schistose structures, as illustrated in Table I. The relation of certain quartz textures to dilation of the opposing vein walls is explained by Johnston [3] and the dilatant character of many intrusive dikes is discussed by Goodspeed.[4]

Structural Deformation of Barren Country Rock.—Portions of the dikes and quartz veins [5] at Grass Valley occupy zones of reverse faults, which are widely distributed and diversely oriented. Only restricted areas along the faults are thus occupied, however, and the barren fault zones commonly extend far beyond, providing

[2] Crane, W. R.: Rock bursts in the Lake Superior Copper Mines, Keweenaw Point, Mich. U. S. Bur. Mines, Bull. 309, fig. 3–31, 1929. Greenwald, H. P. *et al.*: Experiments on strength of small pillars of coal in the Pittsburgh bed. U. S. Bur. Mines, Techn. Pap. 605, figs. 4, 6, 1939.

[3] Johnston, W. D., Jr.: Vein-filling at Nevada City, California. G. S. A. Bull., 49: 29, fig. 3, 1938.

[4] Goodspeed, G. E.: Dilation and replacement dikes. Jour. Geol. 48: 175–95, 1940.

[5] The term "vein" is here restricted to the more or less tabular bodies of gold-bearing quartz and the term "dike" is used for the similar-shaped bodies of other igneous products. Some difficulty is encountered in trying to segregate them except by composition.

TABLE I.

DILATANT ROCK DEFORMATION.

Zone of Static Load.	Appropriate Type of Strain.	Characteristic Dilatant Structures.	Movement on Partings.
		Open rift	99% tension 1% shear
LIGHT	SPLITTING OPEN	Fissures with cracked and sloughing walls	
		Shingled rubble	50% tension 50% shear
		Coarse, open breccia	
	BRECCIATION	Mixed, tight breccia	
		Sandy granules	
		Mixed breccia and gouge	
MODERATE			
		Narrow breccia and narrow gouge	
	COMMINUTION	Wide gouge without breccia	
		Gouge of variable width plus rock shavings (fluccan)	
		Narrow gouge plus drag-folded fluccan	1% tension 99% shear
HEAVY			
	SLICING	Slips and drag folds without gouge	
	SLIPPING	Slips without drag folds	
		Fracture cleavage	
	GLIDING	Flow cleavage	
		Gneissoid deformation	No dilation
OVERLOADED	PLASTIC FLOW	Flow without partings	

abundant exposures of deformed country rock, free from the changes that may be induced by vein-forming processes.

Rock deformation at Grass Valley is recognized most readily in certain laminated members of the old meta-volcanic and meta-sedimentary series. In them, a typical thrust fault, of 10 to 100 feet displacement, exhibits from place to place a gouge from 0 to 8 inches wide, a zone ranging from a few inches to several feet wide of the fluccan and, flanking the central panel of faulting, a fading belt of sub-parallel slips and of drag folds. Where well-defined fault "walls" are lacking, the belt of deformation may be represented either by a schistose zone or by a gneissoid zone, wherein soft, talcose or chloritic bands fill around augen-like masses of hard rock. Sets of closely spaced, smooth slips are found in broad zones across the metamorphic rocks—nearly perpendicular to the foliation, as a rule, and this rhombohedral orientation is preserved through the swirls of drag folds as well

as in monoclinal blocks. Rhombohedral jointing is also common in the younger, igneous rocks and somewhat resembles, but is less perfect than this cross-sheeting of the foliated rocks.

The seams of gouge along a fault zone are of erratic width; at an exposure on the bottom level of the Idaho Maryland mine (Fig. 1) a post-quartz fault gouge tapers from eight inches wide to a mere film within two feet. When it is newly exposed, this gouge contains only about 1 per cent moisture and is of specific gravity between 2.55 and 2.67; the rocks from which it has been comminuted are of specific gravities 2.6 to 2.97, allowing a maximum dilation of only 14 per cent, as contrasted with the 110 per cent dilation developed by comparable comminution at the surface. Although an assay pulp will accept water equal to the increased volume, this gouge is almost impervious to water at first, but slowly swells to a bulky mud during a day or two of immersion. Underground, if a gouge is restrained from swelling and washing away it is a very effective water seal; if not restrained, the gouge may become soaked with ground water and flow or squeeze into mine workings as a mud. At depth, however, certain dry gouges and fluccan ravel from the apparently-solid roof and sidewalls and slide into mine workings as a surprisingly mobile, fine talus.

Geologic deformation in the Sierra Nevada belt is generally restricted to slightly dilatant structures. Brecciated country rock is notably absent along the barren thrust faults and seems to be found underground only as a result of mine blasting and caving (the angular inclusions of country rock or quartz incorporated into dikes and veins are *inclusion breccias,* not necessarily derived by faulting). By an accepted definition[6] "*Fault breccia* is the breccia which is frequently found in the shear zone, more especially in the case of thrust faults." Quite to the contrary, this writer finds fault breccias to be more abundant along the near-surface normal faults (such as the Basin-Range structures) where the fault surfaces are not greatly compressed and may

[6] Lindgren, W.: Mineral Deposits, 3rd ed., p. 152, 1928. The definition is taken from the Committee on the Nomenclature of Faults of the Geological Society of America.

dilate readily; the strongly compressed blocks of the reverse faults glide along without room to dilate sufficiently to allow the formation of breccia masses. For example, in the Bingham and Tintic districts of Utah, certain compressive faults are so obscure that they are recognized more by stratigraphic breaks than by visible partings, gouge or breccia, whereas the adjacent gravity faults are large structures.

At Grass Valley, visibly open fissures are almost never found where pilot headings first penetrate the country rock, although inflowing ground water subsequently may wash away enough fluccan and gouge along a fault to develop an open fissure at the side of the working. Such an opening will impress the occasional visitor and may lead to the misinterpretation that the open fissure is of geologic origin. A mine opening robs the ground water of support and the decompressed, broken rock around the working may even be somewhat deformed by the intruding water as it works down along the porous portions of a fault zone. The deeper levels of mines are relatively dry, however, presumably from lack of porous zones in the loaded rocks, from which all materials of lesser specific gravity tend to be ejected.

An illuminating type of dilatant deformation results from the pressure-grouting of a dam foundation through drill-holes. After filling any pre-existing openings, the grout may intrude and inflate the bedding planes of flexible, shaly sandstones, as if it were magma, forming an igneous sill or laccolith. At Williams, Arizona,[7] the beds are thus flexed without rupture by composite injections of grout and develop narrow " straps " of folded rock between the tips of *en echelon* lenses of grout—a structure that is also found in veins and dikes of the Sierra Nevada. As a parting widens from inflation by the injected grout, it also tends to lengthen by splitting the rock ahead, owing to the greatly multiplied stress at the tip. This mechanism probably is highly effective in the intrusion of magma and vein-forming fluid into country rocks and it may be responsible for the characteristic form

[7] Oral communication by Prof. Raymond E. Davis, who also loaned specimens from his collection at the University of California Materials Laboratory.

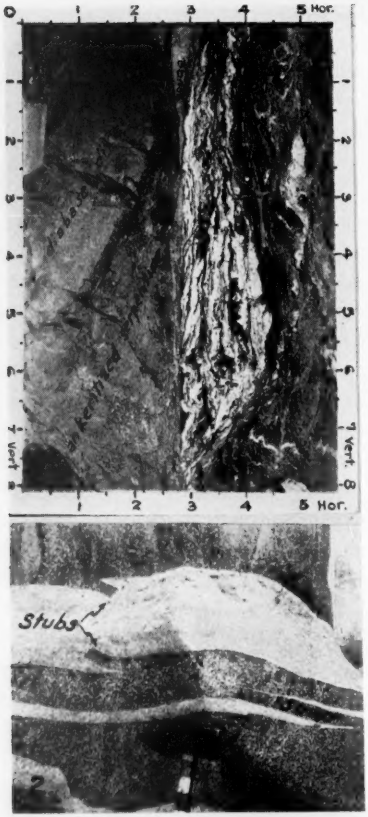


FIG. 1. A faulted segment of a deformed gold-quartz vein (white) to the right of a vertical fault gouge (light gray) of variable width. The gouge at V. 2.7, H. 2.8 is a mere film, but two feet higher, at H. 2.6 to 3.3, V. 0.1, it is 8 inches wide. The 3-ft. diabase dike (upper left) and the ribboned quartz vein both are cut by the fault without brecciation. The black septa included in the vein are of chloritized diabase, rendered gneissoid with the quartz by deformation. (Idaho-Maryland 2400-ft. level.)

FIG. 2. Aplitic dikes that inflate cross-joints in metadiorite. The "strap" of country rock at the lower right is only slightly flexed but the stubs of a former "strap" at upper left flexed considerably before breaking. (South Yuba canyon, below bridge 1707.)

of the dilatant dikes and veins—lenticular panels, resembling sword blades.

Structure of Dikes.—Widely assorted igneous rocks are present at Grass Valley and nearby.[8] Although some of them occur principally in large masses, most occur also in narrow dikes and sills, comparable in size and shape with the quartz veins. The common dike rocks, listed in order of decreasing age, are serpentine, pyroxenite and gabbro, diorite, granodiorite, diabase, aplite, pegmatitic dikes and Tertiary andesite; nearly mono-mineralic masses of epidote, feldspar and chlorite also are found. As a rule, the narrow dikes are sharply demarked from the encasing wall rocks and occupy recognizably dilatant partings in them, as in Fig. 2.

An especially clear exposure of many dikes is found along the river-polished walls of the South Yuba canyon, between Jones Bar and Bridge 1707 of Highway 49. In that locality, a roof pendant of metadiorite contains the dikes in complex groups, whereas the encircling batholith of granodiorite contains only a few simple ones. The dikes are of granodiorite, diabase, aplite, pegmatite, feldspar and quartz, either interbraided or crosscutting; different groups are in parallel systems and in a few places several types of dike material are found within a single parting in the country rock, presumably a composite from injections of several magmas.

Portions of the opposing walls along most of the dikes show characteristic, irregular shapes that would fit together if the intervening dike were removed. These walls are separated diagonally in some cases, but more commonly are opened without much offset. In effect, the country rock has been considerably inflated by the intruding magma that formed the dikes. This inflation is illustrated (Fig. 3) by the radial separation of fragments of a dark inclusion in the granitic rock where it is traversed by a dike. In zones of lit-par-lit intrusion the inflation is cumulative

[8] Lindgren, W.: The gold-quartz veins of Nevada City and Grass Valley districts, California. U. S. Geol. Surv., 17th Ann. Rept., pt. 2: 2–262, 1896. Nevada City special, California, in Geologic Atlas of the United States, U. S. Geol. Surv., fol. no. 29, 1896.

and develops small, transverse, thrust faults. These faults offset early dikes, are intruded by intra-movement magma and in turn are offset by thrusts arising in further inflation from subsequent injections of magma.

A set of converging, lit-par-lit dikelets may be said to become a single dike in book structure where the volume between the intervening wafers of country rock comprises less than 50 per cent of the total volume occupied, as in Fig. 4. Additional structures of interest in dikes at the Jones Bar locality are: angular inclusions of country rock, mineral banding (Fig. 5), comb texture, wide variation in crystal size and a few vugs within quartz masses.

Pegmatitic dikes containing molybdenite are exposed in the canyon of Oregon Creek, near Camptonville. These appear to grade laterally and downward into veins of milky-white quartz containing some pyrite. Although certain sets of the dikes transect some quartz veins they exhibit the complex "crossing" relationship toward others. A third locality, where well-exposed dikes have inflated the country rock, is near the historic covered bridge that spans the South Yuba river at Bridgeport Resort. Many of the dikes exposed in the mines at Grass Valley are too wide to permit ready comparison of opposite walls but the narrower dikes of diabase and of the more acidic rocks occupy clearly dilatant partings.

Deformation of Country Rock Along Dikes.—A certain narrow strip of country rock, separating the tips of *en echelon* dikes, necessarily is considerably flexed during the injection of the magma into the inflating parting. Some of these "straps" of country rock break after flexing considerably and their stubs furnish markers for measuring further relative movement of the opposing walls (Fig. 2). Other "straps" remain unbroken, even where they are flexed as much as 40 degrees at each end. If this deformation had not occurred under great restraining load, the "strap" would be broken into many segments, with gaping, V-shaped notches at each elbow. The coarse mineral grains in the meta-diorite "straps" at Jones Bar would furnish an excellent background for identifying possible cross-fractures of this sort if they were present.

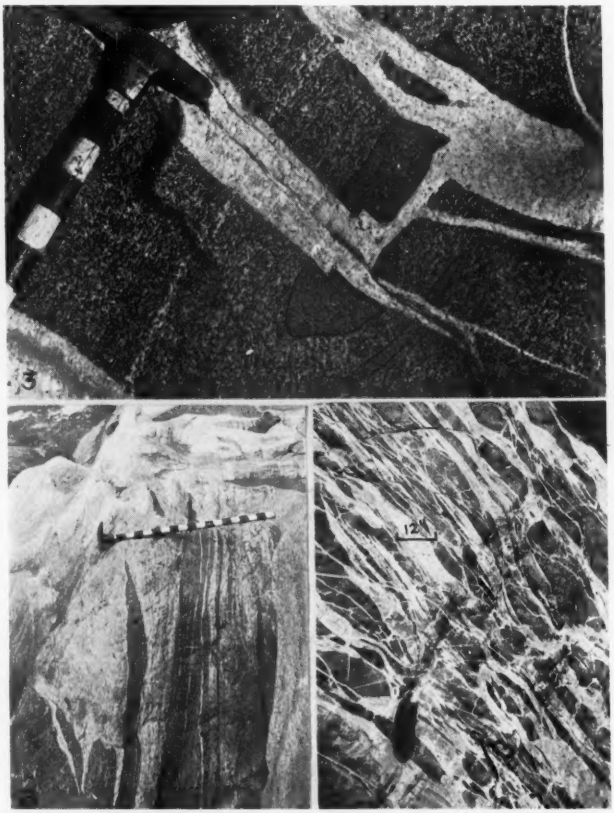


FIG. 3. Lit-par-lit dikes of granodiorite (white) inflating partings that are perpendicular to the foliation of metadiorite. Segments of dark, fine-grained xenoliths are separated by the dikes at the center and give measures of the movements that were involved when the magma invaded the partings. (South Yuba canyon below bridge 1707.)

FIG. 4. (*a*) Aplitic dike, massive beyond the pick but in book structure with the dark country rock at the near end. (South Yuba canyon, below bridge 1707.) (*b*) Light colored granodiorite matrix and dark inclusions of country rock in about equal volume, intermediate between book structure and lit-par-lit. (Along South Yuba river near Bridgeport Resort.)

FIG. 5. Mineral banding in a dike traversing metadiorite in the South Yuba canyon. The bands are alternately quartz and feldspar.

FIG. 6. Pillars of ore in a stope that followed upward along the steep-dipping vein at the right and then benched off along the flat, lit-par-lit veins that emanate from the steep trunk. The junctions of the veins

STRUCTURE OF THE GOLD-QUARTZ VEINS.

The quartz "filling" of the veins usually is described as lenticular, perhaps because most geologic cross-sections show only a lens of quartz along a more extensive fault zone. But "lenticular" fails to indicate the complete downward continuity of the quartz shoots from the top to some unknown bottom which has not yet been reached in mining. The writer has been unable to find one of these long, tapering panels of quartz, of the Sierra Nevada type, which fails to continue down its rake except by faulting or by other post-quartz deformation. Perhaps unsuspected dislocations lie behind some contradictory reports and others may refer only to discontinuous pay shoots.

The quartz (plus about 5 per cent ankerite and 2 per cent metallic sulphides) occurs in long, raking shoots, like sword blades, that commonly are lenticular in cross-section. From them extend a myriad of fin-like stringers and veinlets of the same material, either in ramifying forms or in lit-par-lit groups along zones of sheeting or along sets of joints (Fig. 6). The veins and veinlets are sharply demarked from the encasing wall rock, in many cases by a thin sheath of chlorite, ankerite or sericite and rarely by gold and molybdenite. Many narrow veins occupy unquestionable dilatant partings in the country rock (Fig. 7) and the wide veins probably are similarly dilatant, although it is difficult to secure a measurement of movement in these, owing to a lack of markers in the country rocks.

Fading envelopes of ankerite, sericite, chlorite, pyrite, etc., are diffused into the country rock enclosing the vein "filling," perhaps

present a different pattern from place to place. (Brunswick 800-ft. level, Idaho-Maryland mine.)

FIG. 7. A group of dilatant, lit-par-lit veinlets of white quartz in a dark porphyrite country rock. The flexed "strap" of country rock at V. 2.0, H. 4.0 parted after folding considerably during the "opening" and its stubs give a measure of subsequent movement. A 12-inch rule hangs vertically at the right. The angular fragment at V. 3.7, H. 2.5 would fit the overlying corner but the country rock near the "strap" would not reassemble without unfolding. (Brunswick 1300-ft. level, Idaho-Maryland mine.)

as much by chemical packing from a CO_2-rich gas phase as by a replacement involving the removal of material. The average of many analyses shows 25 to 30 per cent of carbonate minerals in the altered wall rocks. Silicification is rare, however, and apparently is restricted to local zones where carbonate minerals are lacking in the "filling" and in the altered wall rocks. The volume of the silicified (replaced) country rock is very small in contrast to the volume of the quartz "filling"—probably less than 1 per cent.

The vein "filling" is either massive or interspersed with included fragments, septa, and islands of country rock (Fig. 8).

FIG. 8. Ribboned vein (right center) and a sub-parallel, post-quartz, fault gouge and fluccan zone at the left. The ribbon structure is due to inclusions of parallel septa of country rock and of schistose elongation of more angular inclusions during the strike faulting. A 6-inch rule hangs vertically from an open transverse crack in the quartz that has developed during mining operations. (Idaho-Maryland 1800-ft. level.)

Those portions of a vein that are striped are termed "ribboned" by the miners and they may arise from any one or from combinations of the following structural elements:

(1) *Mineral Banding,* resulting from segregation of certain minerals into bands, commonly parallel to the vein.

(2) *Mechanical Sheeting,* from structural deformation of the vein.

(3) *Book Structure,* by inclusion of parallel septa of country rock, inter-leafed with sheets of quartz (Fig. 8). As the included country rock attains more than 50 per cent of the total volume occupied, book structure passes into *lit-par-lit structure.*

(4) *Schistose Structure,* from slipping and recrystallization of the constituents of the vein (Fig. 8).

(5) *Gneissoid Structure,* from the recrystallization of the materials of included country rock around pinched-off augen of the harder quartz (Fig. 9). Crenulated ("pie-crust") borders against the wall rocks and crinkly internal banding mark the gneissoid veins, which revert into veins in straight book structure away from the zone of more intense, post-quartz deformation.

Ferguson[9] finds abundant evidence of recrystallization but notes that ". . . the texture of the quartz in the areas of crinkly banding is not as a rule different from that of other parts of the quartz veins." It is surprising how rarely geologists discuss effects of dynamic and regional metamorphism on veins—many important gold deposits are of pre-Cambrian age and lie between fault blocks of highly metamorphosed rocks. Perhaps the seemingly-late gold has had a sedative action.

Converging veins may either join or intersect, in several apparently-contradictory patterns. At one point along a pair of veins is found simple branching; at the second point is distributive offset of one vein along the other; at the third point is a reversal of the relation at the second point. This diversity is not necessarily owing to different ages of the veins—more probably it is the outgrowth of continued movements of pre-, intra-, and post-quartz age by the several blocks of country rock outlined by the partings, whereby an ever-changing pattern is presented to the entering, vein-forming fluid. Discussions[10] of the relative ages

[9] Ferguson, H. G. and Gannett, R. W.: Gold quartz veins of the Alleghany district, California. U. S. Geol. Surv. Prof. Pap. 172: 78–80, 1932.

[10] Lindgren, W.: *op. cit.,* p. 173. Hoover, H. C.: Some notes on "Crossings." Min. and Sci. Press, pp. 166–7, Feb. 29, 1896. Howe, E.: The gold ores of Grass Valley, California. Econ. Geol., 19: 603, 1924. Knaebel, J. B.: The veins and crossings of the Grass Valley district, California. Econ. Geol., 26: 375–98, 1931. Johnston, W. D., Jr., and Cloos, E.: Structural history of the fracture systems at Grass Valley, California. Econ. Geol., 29: 46 *et seq.,* 1934.

of veins and "crossings" have arisen from this structural complexity.

The "crossing" problem extends to stringer-zone veins and even to intersecting veinlets. For example, the apparently-older

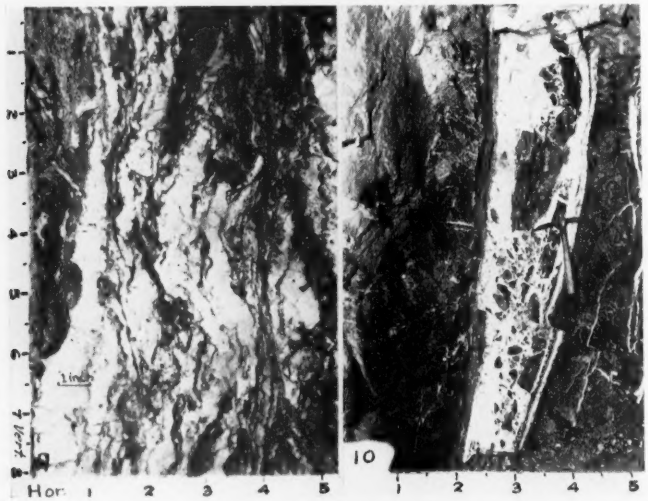


FIG. 9. Gneissoid quartz vein in which augen of quartz are outlined by crenulated septa of included country rock. This structure may be traced laterally away from the deformed zone into a zone of straight-septa book structure. The "pie-crust" pinched borders, V. 7.0 to 3.0, H. 0.0 to 1.0, are characteristic of deformed veins and dikes. (Idaho-Maryland 2400-ft. level.)

FIG. 10. Steep quartz vein and included country rock, cut by a flat thrust fault that extends from H. 5.7, V. 6.3 to H. 2.3, V. 5.7, where it is offset in turn by a later slip along the hanging wall of the vein. The salient of country rock below the pick handle is unbroken whereas the equivalent salient on the lower, hanging wall side of the vein is intimately sliced. (Brunswick 1300-ft. level, Idaho-Maryland mine.)

veinlet on one side of a hand specimen may appear to be the younger on the opposite side. Again, a massive, white quartz stringer may interrupt and separate the halves of a transverse vein showing book structure and appearing somewhat darker than

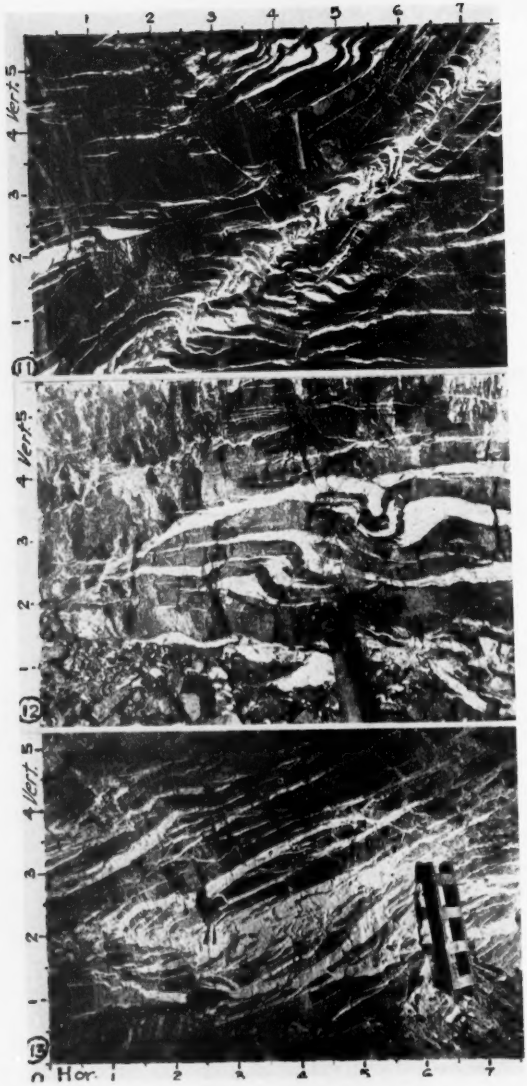
the stringer but no difference in age need be involved, because both veins may grow by simultaneous inflation of the several partings; furthermore, quartz reflects much light if it is massive or shattered and less if dark minerals and country rock are included in it.

Certain fractions of the quartz veins nevertheless show clean-cut difference in age, as where central bands contain mineral species and xenolithic inclusions that are not found in the quartz at the sides. Another example is in wide quartz shoots that engulf and rotate blocks of an earlier vein identifiable by characteristic mineralogy, texture or structure.

Structural Deformation of the Rock Encasing Quartz Veins.—The several varieties of structural deformation that appear in the country rock along the barren parts of fault zones are also to be found along the quartz veins. Some additional types were superimposed during vein emplacement, together with a few that were subsequently developed, owing to the presence of the vein.

The vein "filling" is commonly encased in characteristically serrate partings in the country rock, which would almost exactly fit together if the intervening quartz were withdrawn (Fig. 7). Similarly, groups of adjoining veins or stringers separate irregular blocks of country rock that would reassemble into a compact, interlocking mass, of smaller volume, if the quartz could be retracted from the partings (Fig. 6). In effect, the country rock has been inflated along innumerable partings by the emplacement of the veins.

During the inflation by dikes and quartz veins, the movements along the parting blocks of country rock were highly dilatant and contrast sharply with the post-quartz fault movements, which are zones of slipping involving only slight dilation. The many small movements developed during the progressive inflation of a lit-par-lit group were cumulative and commonly were relieved by oblique thrust faults at the top of the group, whereas the bottom slabs of country rock are not offset. These intra-vein thrust faults are also inflated by the quartz and in turn may be offset by later movements that arose from the further inflation of nearby partings and thus present the complex "crossing" relationships of age.


1 2 3 4 5 6 7
4 Vert. 5
3
2
1
(11)
4 Vert. 5
3
2
1
(12)
4 Vert. 5
3
2
1
(13)
0 Hor. 1 2 3 4 5 6 7

FIGS. 11–13.

Perhaps the best examples of cumulative thrusts are developed by the inflation of closely spaced joints and a connecting transverse thrust fault, in "centipede" structure (Fig. 11). The quartz "legs" on the hanging wall side of the thrust fault are wider and extend ahead of the corresponding "legs" on the footwall side of the growing fault. If the footwall "legs" were wider, a normal fault would be developed; but this is not to be expected because the natural relief of inflation is by uplift of the overlying blocks. Separating the quartz "legs" in the "centipede" are curved slabs of rock outlined by the invaded partings (Fig. 11). The slabs have been markedly folded in some cases and moderately folded along almost every tapered stringer, as may be seen by the concordant folding of the foliation of the schist, which remains nearly at right angles to the partings. In some of the arched slabs, gliding along the planes of foliation permits the flexure without as much rotation of the foliation as would be expected in a perfect fold (Fig. 12).

Where quartz stringers inflate *en echelon* slips, the intervening slab or "strap" of country rock is markedly flexed, in some cases as much as 40° at each end, without breaking (Fig. 11). Thin sections and polished surfaces along the "straps" fail to disclose breaks in many of them and also fail to disclose fractures extending beyond the tips of the quartz-filled joints, which terminate against unbroken, transverse lamellae of the country rock. If

FIG. 11. Lit-par-lit quartz veins forming a diagonal "centipede" structure. The veins inflate slips perpendicular to the schistosity of the country rock. In the folded, inter-vein "straps" the schistosity swirls concordantly. (Brunswick 1450-ft. level, Idaho-Maryland mine.)

FIG. 12. Imperfectly folded slabs of schist outlined by cross slips that have been inflated by quartz veins. The foliation in the folded slabs is generally perpendicular to them but lags somewhat at points of slipping. (Brunswick 580-ft. level, Idaho-Maryland mine.)

FIG. 13. A wide-angle photograph, embracing 100 feet of stope wall. The white gold-quartz veins occupy cross-sheeting partings of the dark schist, in lit-par-lit structure. Support of the cross-grained slabs of country rock across an acre of similar vein structure is a problem for proponents of an open-fissure deposition of the quartz. (Brunswick 800-ft. level, Idaho-Maryland mine.)

the "straps" were arched by rotation of rigid, broken segments, then V-shaped notches should be developed at the turns and, although notches are found at some places, as at V. 3.0, H. 5.8 in Fig. 12, they are lacking in most "straps." If the stringers are of ankerite, instead of quartz, they may be leached away with acid, leaving the flexed "strap" standing unsupported and thereby verifying its unbroken character.

Not all of the "straps," however, remain unbroken by the strain from inflation of the adjoining stringers; many break after flexing considerably and their stubs furnish excellent markers for measuring subsequent displacement of the opposing walls (Fig. 7, V. 2.5, H. 4.3). If the width of the stub is small in comparison with the width of the merging stringers, a nearly straight vein results; if the stub is relatively wide, the merging stringers show a pronounced jog in alignment. The important "strap" structure is almost duplicated by *en echelon* cracks along the grain of drying timbers, except for the significant difference that in timber the "strap" fibres remain straight and the curvature is in the shrunken timber at the sides of the cracks. A flexed "strap" results when a wedge is driven into one of the cracks.

Quartz veins commonly include fragments and septa of country rocks in peculiar relationship to the enclosing walls. Dislocation, rotation and transportation of the inclusions appear to have occurred independent of possible fault movements. The writer has described these features earlier[11] and has suggested that they may result from the sluicing action of an injected, vein-forming fluid. Xenolithic relationship of vein inclusions to the adjoining rocks is found in counterpart in the dikes and in grout deposits. Breccias from which the vein inclusions could be derived are not found along the faults and unquestionably are lacking along the barren partings of cross-sheeting, which nowhere are sufficiently open to accommodate fragments of visible size.

Many quartz veins at Grass Valley are offset by transverse faults (Fig. 10) or are sliced by renewed movements nearly parallel to the pre-quartz faults. Practically all of the faults are

[11] Farmin, R.: Dislocated inclusions in the gold-quartz veins at Grass Valley, California. ECON. GEOL., 33: 579–99, 1938.

reverse—although considerable horizontal components of movement may be involved. These late fault zones exhibit much the same types of deformation that are found along the barren lengths of the older faults, where pre- and post-quartz movements are superimposed. Although erosion may have stripped away many thousands of feet of rock cover between the time of vein formation and the time of post-quartz faulting, the deformation at the later date is only slightly dilatant: it develops gouge, fluccan, zones of slippage, drag folds and gneissoid belts. The most dilatant of the products is the sugary, mashed quartz in the gouges.

INTERPRETIVE DISCUSSION.

The Mechanism of Dike Emplacement.

Volcanology supplies a reliable background of knowledge about the upper ends of dikes and about the near surface activity[12] of magma. Volcanic material of various types rises to the surface and is extruded, along with entrained xenoliths, from partings in the country rock. Whatever may be its nature, the volcanic motivating force is sufficient to elevate the magma to mountain tops, to lift spines as at Pelèe, to blast away a cubic mile of cover over a crater or to split new partings through the base of a volcanic cone if the former vent is blocked.

By geologic backtracking, extinct volcanoes and their underlying, dike-filled vents are traced downward toward the zone where deep-seated dikes and ores are emplaced. For example, 30 miles north from Grass Valley, feeder dikes are intermittently exposed in mines from a point level with the floor of extrusion on down to a depth of 2400 feet below that floor.[13] These dikes occupy dilatant partings similar to those recently described at Cornucopia, Oregon.[14] Because changes in form and texture of dikes are gradual in exposures ranging from near-surface to deep-seated environments, it seems reasonable that the mechanism of emplacement is not greatly different at depth—that the magmatic fluid is

[12] Zies, E. G.: The surface manifestations of volcanic activity. Trans. Amer. Geophys. Union, 19th Ann. Meeting, pp. 10–23, 1938.

[13] Farmin, R.: *op. cit.*, p. 594. Details of the occurrence are described.

[14] Goodspeed, G. E.: *op. cit.*, p. 176, 1940.

propelled through the partings of the host rock by a fully adequate telluric force. Where this is the case, the structures of the dilatant dikes are readily explained as resulting from a progressive magmatic inflation of the host rock along zones of sheeting, along folia and along irregular partings. The process involves uplift of overlying blocks and involves thrust faulting, minor folding and metamorphism of the wall rocks. The dike-forming minerals crystallize from the fluid without allowing much deflation of the distended fissures, judging from the lack of collapse breccia and relaxational faults.

The concept that the injected magmatic fluid is a wet mush of partly formed crystals [15] seems to fit many features of the deposits, but the comb textures and mineral banding are not readily explained by it unless they have resulted from recrystallization.

Reasons for concluding that the mechanism of dike emplacement is a forcible intrusion, not limited to loci of pre-existing openings, are (1) the general inflation of the host rock by dikes is not limited to partings in the "tension" position, (2) intramagmatic fault offsets are either reverse or simply dilatant, (3) the slicing and separation of the country rock into slabs in lit-par-lit and book structure and the folding of the inter-dike "straps" of country rock could not develop along the unloaded surfaces of an open fissure, (4) the inclusion by dikes of angular fragments of the wall rocks indicates intrusion because these rocks nowhere are found to be brecciated by the structural deformation along barren faults and folds.

The Mechanism of Vein Emplacement.

Several mechanisms have been suggested to explain emplacement of quartz veins in the Sierra Nevada gold belt. The first three discussed here are variations of the "hydrothermal hypothesis," the last is the hypothesis of a magmatic injection.

1. *Replacement.*—Although the replacement mechanism has been advanced for the veins of Grass Valley,[16] its general effect-

[15] Sosman, R. B.: Evidence on the intrusion-temperature of peridotites. Amer. Jour. Sci., V, XXXV-A: 359, 1938.

[16] Howe, E.: The gold ores of Grass Valley, Calif. ECON. GEOL., 19: 595–622, 1924.

tiveness must be very limited in view of the almost universally dilatant character of the partings occupied by the quartz. The metamorphosis of the wall rocks adjacent to the quartz veins to an ankerite-chlorite-sericite-talc rock involves abundant addition of carbon-dioxide (by diffusion ?) but perhaps does not involve the withdrawal of an equivalent amount of material because the system shows increase in volume, shows increase in specific gravity of the altered rock and because no elements seem to have been eliminated by the process.

2. *Lateral Secretion.*—The derivation of some of the materials for vein filling from wall rocks (not necessarily adjacent to the point of deposition) has been suggested by Knopf [17] as an auxiliary mechanism in vein formation. Even if it is coupled with the linear force of growing crystals, lateral secretion does not offer a mechanism for the transportation of xenolithic inclusions nor for the folding of "straps" and therefore cannot be more than an incidental feature of an hydrothermal deposition.

3. *Accretion from Hydrothermal Deposition in Reopened Partings.*—The accretion mechanism (progressive deposition from dilute hydrothermal solution in partings opened by the bridging of fault walls) has been the backlog for most geologic interpretations of the quartz veins. It seems to explain some segments of veins and the alteration of wall rocks admirably; and it offers much freedom for explaining the complex microscopic textures to which many geologists not actively engaged in mining devote considerable attention.

Along the larger veins the specific information about pre-, intra-, and post-mineral faulting movements seldom is sufficiently well known to permit a rigorous test of the accretion hypothesis. Fortunately, however, satisfactory measurements of these movements are available along the subordinate veins, spurs and stringers that have contributed a respectable proportion of the gold mined in California. The partings that encase these parts of the veins commonly are mere slits in the rock, showing only microscopic lateral offsets but containing quartz an inch or two wide

[17] Knopf, A.: The mother lode system of California. U. S. Geol. Surv. Prof. Pap. 157: 32, 1929.

that tapers to the very tips of the partings; beyond the tips the counry rock is unbroken, as has been verified by thin sections and by acid leaching of the carbonatized rock. Obviously, diagonal thrusting does not explain the development of these openings, which are one hundred times wider than the total lateral movement involved. Therefore, the structural preparation of openings that is fundamental in the accretion mechanism is found to be lacking in most of these stringers.

Further structural difficulties are encountered when the accretion mechanism is offered to explain the " straps " of country rock lying between veins or to explain the flexed slabs of wall rock in the " centipede " veins. The dense rocks that are host to the veins cannot be flexed appreciably except under great restraining load—which is absent in an open fissure. The partings occupied by the quartz are smooth, shear-type joints that are discordant with open fissures and, although similar smooth partings are abundant in the barren country rocks, tensile openings are not found in them, nor are breccias found consequent to the collapse of such openings.

At first glance, both book and lit-par-lit structures seem to be well explained by the accretion mechanism. According to the statement by Hulin: [18]

> Portions of the Mother Lode contain innumerable thin oriented parallel fragments of the foliated wall rocks. At times these are spaced only a small fraction of an inch apart through vein thicknesses of several feet. This "book structure" could conceivably have resulted only through countless reopenings of the vein fissure contemporaneous with the mineralization, each reopening tearing loose a thin film of the foliated wall rock which had frozen to the vein.

A criticism of this mechanism is that the foliated country rocks always lie at an angle to the veins and only locally are dragged into approximate parallelism; therefore, the rock wafers are not folia pulled apart by vein opening because they are cross-grained and would open only as ragged masses. Instead, the wall rocks have been self-sliced in a shear-type deformation requiring great restraining load and subsequently have been leafed apart to receive the quartz. Many of the slabs are flat-lying, cross-grained masses

[18] Hulin, C. D.: Structural control of ore deposition. ECON. GEOL., 24: p. 30, 1929.

of large area (Fig. 13) that would not be self-supporting for an instant if a tensile opening were to rob them of support and most assuredly would not withstand the slicing process except under load. Whether the slicing and opening by the accretion mechanism is thought of as a progressive or as an alternating process, it seems to be geologically discordant and mechanically unsound.

It may be suggested that ground water penetrates to the zone of sliced ground and supports the rock slabs during an accordion-like opening and until the arrival of the hydrothermal fluid. Although some support would be delivered to the walls in this case, the flat-lying slabs nevertheless would break and sink in a water free to displace upward in the fissures. Furthermore, the interchange of support from one fluid to another without damaging the slabs would be a remarkable feat of geologic juggling.

A certain combination of diverse structures occasionally is found in ribboned veins: angular inclusions of the several country rocks, together with the " late " sulphides, occur in a central panel of the quartz vein, sandwiched between marginal panels that exhibit delicate book structure but lack the sulphides. By the usual statement of reopening, the septa of country rock are pulled successively from the walls and therefore the marginal panels should be younger than the central ones, instead of older as is indicated by the mineralogy. Moreover, the angular inclusions will not refit into the smooth walls nor into the adjoining smooth, included septa; and in flat-lying veins the fragments could not tumble far in the narrow spaces available between ribbons. The angular inclusions cannot be remnants from incomplete replacement of a large central slab of included country rock because they are of heterogenous rock types. Therefore, the accretion mechanism does not seem to offer a good explanation for this complex structure.

A further test for the accretion mechanism is in the occurrence of quartz in continuous shoots that maintain fairly uniform dimensions and lenticular cross-section for impressive lengths along the rake. Because the veins are limited to fault openings by the hypothesis, it is necessary that the faults—while traversing

hard and soft rocks of various sorts—maintain a succession of arched openings that are aligned, side to side, without interruption by a compression belt, through the mile or two known to us from mining. Moreover, the unbroken tension bridge must have extended on down to the igneous hearth and on up to the surface; and it must have endured through the very long period of accretion of the quartz and until the " late " metallic sulphides and gold were added. Bearing on this last requirement is the fact that extensive mining of many quartz veins at Grass Valley shows a persistent 1 to 3 per cent tenor of these seemingly-late minerals in the ores; perhaps half of all of the quartz that has been exposed contains these " sulphurets " to the amount of 1 per cent. Therefore, the shoots must have been open or reopened throughout most of the time in order to receive so widely the " late " minerals in overlapping sequence. Thus, the entire accretion mechanism depends on the favorable alignment of coincidences for each second it operates—that chance would permit the accretion of more than one such shoot in a district seems a very remote possibility.

A further stumbling block is the fact that sizeable deposits of the " late " minerals without much quartz are so rare along the intra-mineral faults. Surely if separate solutions [19] brought these materials, at intervals they should have escaped into newly formed fault openings, especially if reopening of faults is made a basis for the mechanism.

Even the " plumbing " for a hydrothermal " circulation " is obscure. How are the vein trunks filled—from top to bottom or bottom to top, from side walls inward or from a central panel outward? These questions bear on a possible blockage of the hydrothermal flow and the consequent incomplete filling of the veins (to be expected far in excess of the small, ellipsoidal, disconnected vugs that are found in them). It seems difficult to avoid a blockage of flow of the solution from the trunk channels into the broad, leaf-shaped stringers, which commonly are attached to the sides of the vein trunk only by narrow stems. Stringers of this shape present a real problem in the " plumbing " for a con-

[19] Hulin, C. D.: Structural control of ore deposition: the effects of mineral sequence. Abstract, ECON. GEOL., 34: 471, 1939.

tinued "circulation" of the hydrothermal fluid throughout the long period of vein accretion and enrichment. Lindgren[20] discounts the importance of filling by diffusion through stagnant solution and Graton[21] stresses the necessity for a long-continued flow of the solution past all points of deposition. Many veins and stringers are "frozen" fast to their walls and seem as impervious as the dense country rocks; a system of "plumbing" for packing them so tightly from end to end by hydrothermal flow should not be taken for granted.

Evidence for "openings" from bridging fault surfaces should be found if they have been formed on a scale to accommodate the rotation and transportation of six-foot slabs of country rock as vein inclusions; however, such openings, and the breccias that would develop by their collapse, are lacking. Instead, the zones of dilation along the thrust faults apparently were filled at all times with gouge, fluccan and similar products; and the fault blocks glided along the undulating surfaces somewhat after the manner of moving glaciers rather than as inflexible masses. In this geologic environment actual openings are discordant; and volumes such as those occupied by the veins are not passively yielded by the country rocks. Gouge is here pictured not only as the product of abrasion but also as a fluff of rock splinters[22] spalled from the decompressed fault surfaces where diagonal movement tends to separate them. The irregular masses of gouge and fluccan measure the dilation involved in a fault movement and fill the only "openings" made available for the accretion of vein matter.

4. *Host-Rock Inflation by a Vein-Forming Magmatic Fluid.* —A few geologists have advocated vein formation by the mechanism of an intrusive, magma-like fluid, or slush, from which the gold-quartz veins crystallize. In an excellent paper[23] on the nearby veins of Alleghany, Ferguson partially endorses such a

[20] Lindgren, W.: Mineral deposits. 3rd ed., p. 201, 1928.

[21] Graton, L. C.: The nature of the ore-forming fluid. ECON. GEOL., 35: 320, 1940.

[22] Willis, B. & R.: Geologic structures. 2nd ed,, pp. 446–8, 1929. A discussion of the work of Bridgeman and others on the failure of rocks under pressure.

[23] Ferguson, H. G. and Gannett, R. W.: Gold quartz veins of the Alleghany district, California. U. S. Geol. Surv. Prof. Pap. 172: 85, 1932.

mechanism, conditional upon the non-recrystallized character of the vein textures. He puts his finger on the basis for most of the current objections to the intrusive hypothesis (p. 83) as follows:

> Another difficulty . . . seems to lie not in its failure to fit the observed conditions but in the question whether the existence of a magma composed essentially of silica . . . is possible.

These objections are based on laboratory experimentation under conditions that do not even approximate the magmatic environment; patently, no finality attaches to them.

The geologic parallel between the aplitic-pegmatitic dikes and the gold-quartz veins is strikingly close in the Grass Valley district. Some of the features exhibited by both are:

(1) Mineral banding, sheeting, schistose, gneissoid, book and lit-par-lit structures.

(2) Mineral constituents in common: quartz, orthoclase, albite, epidote, muscovite, pyrophyllite, chlorite, scheelite, pyrite, gold, molybdenite.

(3) Deposits of the same size and shape, surrounded by envelopes of altered wall rocks. Along the Sierra Nevada belt the tonnage of quartz veins probably equals or exceeds the tonnage of the aplitic-pegmatitic dikes.

(4) Continuity of deposits from top to bottom, along persistent, raking panels, with constituent minerals rather well distributed throughout.

(5) Drag-folded wall rock along the partings occupied; localized zones of folding of walls during the deposition, as around blunt spur stringers and as in the "straps" between *en echelon* stringers.

(6) The inflation of sets of shear-type joints to accommodate lit-par-lit deposits; and the inflation of all partings occupied without restriction to those in the "tension" position in the ellipsoid of strain.

(7) A parallel structural response to variations in the character of the country rock traversed—simple, tabular forms in granodiorite, opposed to the book structure, ramified and lit-par-lit forms in the jointed, metamorphic rocks.

(8) Contact or inclusion breccias of angular fragments of country rock, in part xenolithic, are developed during the emplacement of the deposits in country rocks that elsewhere are not brecciated by faulting.

(9) The thin wafers of country rock included as book structure in veins and dikes commonly are sliced at an angle to the foliation of the rock, implying the operation of a mechanism other than reopening.

The foregoing, many-sided geologic parallel between dikes and the gold-quartz veins constitutes a strong argument for parallel origins and parallel mechanisms of emplacement for both. This deduction by analogy may be weak, as reasoning goes, but the "hydrothermal hypothesis" is equally vulnerable, being based on an analogy between our water chemistry of the laboratory and the complex physical chemistry of magmatic processes plus the questionable assumption that sizeable openings of specialized shape remain open for vein deposition, from the magmatic hearth to the earth's surface, for a long span of time.

For each of the structures that are exhibited both by dikes and veins, the inflation mechanism is a convincing explanation, proved workable by the magmas that come within our range of observation. Aside from possible differences in the phase and composition of the injected fluids, the structures and textures of the resulting deposits are parallel and continuous. Geologically, dikes and the quartz veins form a series of deposits that should be graded by composition only. No break is apparent in the series, such as would be expected where a dilute solution separates from the concentrated parent magma and where the process ceases to be intrusive and becomes permissive.

The complex, microscopical detail of vein textures may not be matched throughout, in counterpart, by dike textures although the parallel seems to be nearly complete. If the microscopic space relations between the mineral particles in a few cubic millimeters of ore is expanded into a geologic history that seems to be capped by the late, almost-accidental addition of the gold and metallic sulphides, then some error surely has crept into the interpretation.

Such an interpretation ignores the widespread cohabitation of these seemingly-late minerals with the gangue, in tremendously ramifying deposits, and the consequent implication of a joint deposition. Furthermore, the paragenetic "sequence" of minerals is much the same in most of the gold-quartz deposits of the world, many of which are of pre-Cambrian age and now are of metamorphic character. Since the "sequence" survives metamorphism, it probably is not the order of importation of these materials to the site of deposition but instead expresses some property of the minerals that governs paragenesis during the primary crystallization under hydrostatic stress and also during recrystallization under differential stress.

The paragenetic "sequence" is also a list of the minerals present in order of decreasing hardness [24] and it may be expanded to include many of the non-metallic gangue minerals, some of which are "later" than the gold—and softer. Polished sections of rich ore show gold and petzite not in veinlets but rather in spidery and holly-leaf masses, nested between quartz and ankerite grains. These masses are discontinuous and are neither the fillings of dilatant fissures nor the expectable forms of replacements or vug fillings. Instead, they suggest the forms that would develop in soft minerals squeezed between hard minerals during a leisurely metamorphism. The observed paragenetic relation thus could result from the schistose or gneissoid deformation of minerals that had first crystallized nearly simultaneously. Certain fractions of the deposits show little evidence of a general deformation, however, so a paragenetic control geared to mineral hardness needs to operate likewise at the time of deposition, under nearly hydrostatic pressure.

The suggestion of a primary control of paragenesis by some property geared to mineral hardness is offered principally to illustrate the possibility of finding a simple explanation for the world-wide "sequence" of ore and gangue minerals in veins. Some such new interpretation is needed to explain the seemingly-late

[24] Bandy, M. C.: A theory of mineral sequence in hypogene ore deposits. Econ. Geol., 35: 375, 1940. "The physical properties of the sulphides were examined but, aside from hardness, no other property was generally consistent."

paragenesis of gold in the Sierra Nevada, at the Witwatersrand, and other districts, where the late addition of an independent gold seems inconsistent with the general geology of the deposits.[25]

The writer can offer no firm conclusion concerning the composition of the fluid from which deep-seated quartz veins are deposited. A rank guess could be based on the ratio of "filling" of quartz to the volume of material added to the altered wall rocks. On this basis, the fluid may contain 10 to 40 per cent SiO_2 before the supplementary, volatile fraction presses on into the pores of the wall rock, perhaps as a CO_2-rich gas phase. The SiO_2 did not join in this penetration and therefore may have been restricted to the liquid and solid phases.

SUMMARY OF CONCLUSIONS.

1. Geologic deformation of the country rocks in the Grass Valley region has not developed extensive open partings of the size and character necessary to accommodate the abundant dikes and quartz veins, nor has faulting produced brecciated rock fragments of the sort that now are angular inclusions in the veins and dikes.

2. Portions of the rock encasing the veins and dikes have been folded concurrently with the inflation of the partings occupied—a type of deformation discordant with open fissures.

3. Deposition of the veins by the mechanism of a quiet, "hydrothermal accretion" in reopened faults is considered improbable because in many of the veins the necessary structural preparation is lacking.

4. Vein deposition through inflation of partings in the country rock by an injected, quaisi-magmatic fluid is the mechanism which best explains the occurrence. The many-sided, geologic parallel between the closely associated veins and dikes of the region embraces most of their structures, textures, mineral species and habits of environment; this parallel constitutes a strong argument for

[25] Ödman, O. H.: Late gold and some of its implications. ECON. GEOL., 33: 772–5, 1938. duToit, A. L.: Developments on and around the Witwatersrand. ECON. GEOL., 35: 106, 1940.

parallel origins and mechanisms of emplacement. For each of the parallel features, the dikes offer a concrete proof of the workability of the inflation mechanism that is suggested for the emplacement of the veins.

5. The paragenetic "sequence" of ore and gangue minerals does not necessarily imply an independent, late importation of the gold and other seemingly-late materials into the vein. Instead, the "sequence" may express some fundamental property of the minerals, geared to hardness, which survives metamorphism. The hypothesis of a late, independent introduction of the gold, metallic sulphides and the softer gangue minerals is inconsistent with their wide distribution through tremendously ramifying vein systems.

IDAHO MARYLAND MINES CORP.,
GRASS VALLEY, CAL.,
Sept. 15, 1940.

NOTES ON THE OCCURRENCE OF GUDMUNDITE.

EDWARD SAMPSON.

ABSTRACT.

Gudmundite, the antimony equivalent of arsenopyrite, is a mineral of more widespread occurrence than is commonly recognized. A mineral, probably gudmundite, has been reported from Yellowknife, Northwest Territories, Canada. The known properties of gudmundite from all known localities are reviewed and brief notes given as to geological associations.

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INTRODUCTION.

AFTER the completion of the laboratory work on the ores of the Yellowknife district, in the Northwest Territories, Canada, by Mr. Carman Ridland, published in a preceding paper, and his departure for further field work in that area, several papers have come to my attention that describe additional occurrences of the little known mineral, gudmundite, and the following brief notes are offered as a supplement to Ridland's paper, as it has been impossible for him to carry the study further himself at this time.

RECORDED PROPERTIES OF GUDMUNDITE.

Locality.	Gudmundstrop Johansson, Buerger.[1]	Bjurliden and East Högkulla Gavelin.[3]	Gudmundstorp and Bjurliden Ramdohr.[4]	Yellowknife Ridland.[6]
Chemical composition	FeSbS	Fe, Sb, S Cu and As absent.		Fe, Sb, S As very faint to negative. Ni, Co negative.
Crystallography, etc.	Monoclinic[2] A, 10.00 Å; B, 5.93 Å; C, 6.73 Å. $\beta' = 90°$ 00′. Formula weights per cell, 8 FeSbS. Calculated density 6.93. With Buerger's orientation, observed forms: (101), (110), (101), (130). Habit: prisms // *c*, with (130) strongly developed.	Needle-like crystals, elongated apparently // *a* axis (which with Buerger's orientation is the *c* axis).		Diamond-shaped sections. Most grains irregularly bounded. Twinning common.
Polish		Slightly harder than pyrrhotite and sphalerite. Much softer than arsenopyrite.	$H = 4$; similar to pyrrhotite, perhaps harder. Polishes readily, better than arsenopyrite.	$H = F$; very hard, apparently same as arsenopyrite.
Reflectivity, color		Pure white, like arsenopyrite.	Reflectivity, high; higher than arsenopyrite. Almost pure white. In oil, paler color, towards rose.	Brilliant white. Like arsenopyrite.
Reflection pleochroism		Clear, especially in oil. A little stronger than arsenopyrite.	Clear; pure white to rose-white and darker; in oil somewhat stronger. // *c*[5] (*i.e.* // the striations of the prism), pure white, perhaps a trace of pale green; // *a*, pale rose (similar to pyrrhotite, but whiter and brighter); // *b*, rose-white.	No pleochroism.
Crossed nicols		Pure white to pale brown, similar to pyrrhotite, though paler. With violet filter a little stronger than arsenopyrite.	Strong like arsenopyrite with clear color distinctions.	Strongly anisotropic. Two extinctions per revolution. Polarization colors vivid; white, gray, green, blue, black, purple, pink, brown.
Etch properties				HNO_3—slow in starting, stains gray then iridescent, then black with effervescence. HCl, KCN, $FeCl_3$, KOH, and $HgCl_2$ negative.

[1] Johansson, K.: Gudmundite, ein neues Mineral innerhalb der Markasitgruppe. Zeit. f. Krist., 68: 87–92, 1928.

[2] Buerger, M. J.: The crystal structure of gudmundite (FeSbS) and its bearing on the existence field of the arsenopyrite structural field. Zeit. Krist., 101: 290–316, 1939. On the basis of studies on Gudmundstrop type material, Buerger demonstrates monoclinic symmetry for the arsenopyrite group and reorients the entire arsenopyrite group including Johansson's orientation.

[3] Gavelin, Sven: Auftretten und Paragenese der Antimon minerale in swei Sulfid-vorkommen in Skelleftefelde, Nordschweden. Sveriges Geol. Undersökning. Ars., 30 (1936), no. 11.

[4] Ramdohr, Paul: Erzmikroskopische Untersuchtung an einigen seltenen oder bisher wenig beachteten Erzmineralen. Tiel I. [Section on gudmundite.] Zentralblatt f. Min. etc., 1937 pp. 203–204.

[5] Buerger's orientation.

[6] Ridland, G. C.: Mineralogy of the Negus and Con mines, Yellowknife Northwest Territories, Canada. ECON. GEOL., 36: 45–70, 1941

The occurrence of gudmundite in the ores of the Yellowknife district is of interest, not only as being the first recorded in North America but as occurring under conditions somewhat different from those described elsewhere. Furthermore, its great similarity to arsenopyrite and its difficulty of distinction from arsenopyrite (a microchemical test is required) suggest, as Ramdohr has pointed out, that it may be much more common than the few records of occurrence indicate. Therefore, a very brief summary of the known occurrences is given.

PROPERTIES OF GUDMUNDITE.

Below is given a summary of the properties of gudmundite as recorded. The various observations are in excellent accord except for the greater hardness of the mineral at Yellowknife, and the lack of ordinary pleochroism at the same locality. However, as hardness is such a fundamental property of a mineral, the possibility must be borne in mind that the Yellowknife material may be a new mineral of different ratios from gudmundite. It has not been possible to secure sufficient material from Yellowknife to permit of quantative chemical analysis.

OCCURRENCES.

Gudmundstorp.—Gudmundite was first described in 1928 by Johannson[7] from a prospect pit at Gudmundstorp, 3 km. from Sala, in central Sweden. Small masses of galena, sphalerite, and minor boulangerite occur in a skarn that also carries a little scattered arsenopyrite. Gudmundite is found in late calcite veins which contain also a little pyrite.

Mineral sequence at Gudmundstorp, Sala district Sweden.

Early	Galena Sphalerite Arsenopyrite Boulangerite	Late	Galena Calcite Gudmundite

In the Skellefte area from 1937 to 1939, gudmundite was described by Sven Gavelin, Ödman, and Ramdohr from 4 localities

[7] Johansson, K.: *op. cit.*

pp. 203–204.
[5] Buerger's orientation.
[6] Ridland, G. C.: Mineralogy of the Negus and Con mines, Yellowknife Northwest Territories, Canada. Econ. Geol., 36: 45–70, 1941

of this mineral region [8] of northern Sweden. These localities cover a range of 52 kilometers along the general strike of the region.

Bjurliden and East Högkulla.—These two camps are respectively 36 and 45 kilometers WNW. of Boliden. Sven Gavelin describes [9] in detail the mineral associations of gudmundite at these places. He gives as representative chemical composition of the main ore body at East Högkulla the following: [10]

FeS_2	17.70	PbS	1.27	Sb_2S_3	.28
FeS	42.20	Cu_2S	.22	Ag	.01
ZnS	38.00	FeAsS	.32		

A suite of minerals in which Sb, Pb and Cu are concentrated occurs as a clearly later generation. These minerals are apparently disseminated through the old zinc-iron sulphides, but may also form individual veins which cut across the banding of the older ore.

The mineral sequence, as I interpret Gavelin's description is summed up as follows:

Magnetite	Arsenopyrite	Galena
Ilmenite	Stannite	Geochronite
Pyrite	Jamesonite	Gudmundite
Pyrrhotite	Bournonite	Bismuth
Sphalerite	Tetrahedrite	Electrum

Ramdohr, under whom Gavelin made his first study of these ores, sums up Gavelin's lengthy description of relations as follows: [11]

1. Eutectoid with pyrrhotite, with proportions of 1:1. It is here commonly in a reaction margin with pyrrhotite of precipitated fahlerz. 2. In a peculiar kind of ice-flower form embedded in bournonite and galena and indicating a replacement of bournonite. 3. Idiomorphic, in galena, calcite, and rarely, also in sphalerite. 4. Formed by precipitation from fahlerz.

[8] For geology and an excellent map showing the localities described here, see Högbom, Alvar: Skelleftefältet, Sveriges Geol. Undersök., Avh. Ser. C., no. 389, 1937.

[9] Gavelin, Sven: *op. cit.*

[10] The analysis from which this is recalculated by Gavelin contained 3.5 per cent SiO_2 and .89 per cent CaO.

[11] Ramdohr, Paul: *op. cit.*, p. 204.

Boliden.—The complex mineralogy of the ores of Boliden also in the Skellefte district has been described by Ödman.[12]

He divides the main ore deposition into three stages: 1, arsenopyrite ore; 2, lamprophyre with quartz tourmaline veins; 3, pyrite ore. Each of these groups contains a complex succession of nonmetallic and metallic minerals. Only the first group, arsenopyrite ore, carries gudmundite although both the succeeding groups carry other sulphantimonides. Ödman lists the minerals of the first group as follows:

Arsenopyrite	Boulangerite	Cobaltite	Quartz	Hornblende
Chalcopyrite	Galena	Saflorite	Rutile	Calcite
Pyrrhotite	Tetrahedrite	Gudmundite	Apatite	Titanite
Sphalerite	Cubanite	Bismuth	Sericite	Andalusite
Pyrite	Valleriite	Gold (electrum)	Chlorite	Plagioclase

Holmtjärn.—At the Holmtjärn locality,[13] also in the Skellefte district, and 55 kilometers northwest of Boliden, a small body of very high-grade gold ore has been mined out. The ore-body consisted of two parts: in the hanging wall, massive arsenopyrite, veined by chalcopyrite; and in the footwall, heavy pyrite. The arsenopyrite was followed by pyrite, with chalcopyrite and a number of other minerals. Among these are the lead and antimony minerals galena, boulangerite, tetrahedrite, bournonite and gudmundite, of which the first three are the most abundant. Ödman makes an observation similar to that of Gavelin, that the content of Sb in the solutions decreased during the deposition of the Sb-bearing minerals, the final product of the solution being galena. My interpretation of the sequence as presented by Ödman is summed up below:

Mineral sequence at Holmtjärn, Skellefte district, Sweden:

Rutile	Tourmaline	Boulangerite	Chalcopyrite
Pyrite	Pyrite	Galena	Pyrargyrite
Arsenopyrite	Pyrrhotite	Bournonite	
Chalcopyrite	Sphalerite	Tetrahedrite	
Gold	Stannite	Gudmundite	

[12] Ödman, O. H.: On the mineral associations of the Boliden ore. Geol. Fören. Stockholm, Förhandl., 60: 121–146, 1938.

[13] Ödman, O. H.: The gold-copper-arsenic ore at Holmtjärn, Skellefte district, N. Sweden. Geol. Fören. Förhandl. Bd. 61 H. 1: 91–111, 1939.

Snåttermyran, Eastern and Middle Bjurfors Ore Bodies, and Osterbäken.—

Sven Gavelin published in 1939 [13a] a very detailed study of the Malånäs district, lying at the west end of the Skellefte region. This district includes the localities Bjurliden and Ö. Högskulla mentioned above and also the following localities where gudmundite is recorded: Snåttermyran, Eastern and Middle Bjurfors ore bodies, and Osterbäken.

Gavelin sums up the occurrence of gudmundite in the whole group of deposits as follows: [13b]

> In some cases gudmundite occurs as idiomorphic crystals, either forming single grains or in aggregates or bundles of well-defined needles. Though the mineral in the development mentioned often is directly surrounded by pyrrhotite, sphalerite or gangue, it is also in these cases closely associated with galena-veinlets rich in antimony minerals. Gudmundite occurs comparatively often along the contacts between pyrrhotite and tetrahedrite. The textures strongly suggest that the origin of this type of gudmundite is due to corrosion of pyrrhotite by the antimony-bearing ore solution, tetrahedrite and gudmundite being formed almost contemporaneously. In these cases very regular intergrowths between gudmundite and pyrrhotite often occur.
>
> Gudmundite is also formed by the replacement of bournonite by galena in which case it occurs in the bays in the corroded bournonite but is entirely surrounded by galena. It then has the shape of ramiform crystal aggregates. Some chalcopyrite and pyrrhotite is generally also present in this type. In very rare cases, finally, gudmundite is doubtlessly a product resulting from the breaking down of tetrahedrite, when it forms intergrowths with chalcopyrite and pyrrhotite.

Jakobsbaken.—Ramdohr records [14] the occurrence of gudmundite at Jakobsbaken, near Sulitelina, in Norway. The deposit as a whole is heavy pyrite carrying chalcopyrite and emplaced in schistose rocks. The associated silicates indicate intermediate to high temperature for the main mass of the ore. Ramdohr's paper deals with mineralogical details some of which are of great

[13a] Gavelin, Sven: Geology and Ores of the Malånäs District, Västerbotten, Sweden. Sveriges Geol. Undersökn., Ser. C, No. 424, 1939.

[13b] Gavelin, Sven: op. cit., pp. 81–82.

[14] Ramdohr, Paul: Antimonreiche Paragenesen von Jakobsbaken bei Sulitelma. Sonderabdruck aus Norsk geologisk tideskrift, 18: 275–289, 1938.

interest. I list the minerals present as he gives them without attempting to put them in their proper sequence:

Native antimony	Pyrite	Dyscrasite	Jamesonite
Electrum	Arsenopyrite	Chalcopyrite	Fahlerz
Sb-bearing silver	(danaite, a cobalt-	Cubanite	Ag—fahlerz
("Kubischer Dys-	rich variety)	Valleriite	Geochronite
crasit")	Löllingite	Chalcostibite	Pyrargyrite
Pyrrhotite	Gudmundite	Bournonite	Rutile
Sphalerite	Galena	Boulangerite	

Gudmundite, according to Ramdohr is formed in part in intimate intergrowths resulting probably from "complex unmixing." Fahlerz, chalcopyrite, arsenopyrite, and gudmundite are closely associated in one type of structure. The gudmundite and arsenopyrite belong to a series of minerals formed by rearrangement of components of fahlerz ("somewhat Fe- and Zn-bearing, As, or As-Sb fahlerz") and chalcopyrite. Ramdohr recognizes the possibility of the introduction of Fe and the reduction of As, S, and Cu during the process.

Ramdohr also notes the presence of gudmundite formed at a very late stage in much older pyrrhotite. Only ruby silver and dyscrasite-bearing veins are younger.

In common with other districts one notes groups of minerals (1) Early high temperature sulphides pyrrhotite, pyrite, chalcopyrite (here with cubanite and valleriite in exsolution) and rutile. (2) Arsenopyrite. (3) Galena and lead sulphantimonides. (4) Very late, and minor, ruby silver etc. The gudmundite appears to belong in group (3).

Vigsnaes.—Ramdohr also records in the same paper a note on the occurrence of gudmundite at Vigsnaes, on the island of Kamö near Stavanger, Norway. de Launay describes[15] the deposit as heavy pyrite lying in schists cut by gabbro. Copper is present as chalcopyrite and a little sphalerite is noted.

Ramdohr notes a late galena-rich stage with the introduction of Sb and considerable Bi as native bismuth. Sb is in part as native antimony. "Gudmundite forms on older pyrrhotite; intermediate stage chalcostibite shows reaction veins against galena."

[15] de Launay, L.: Gites mineraux et métallifères, 2: 661–662, 1913.

Turhal.—A peculiar occurrence of gudmundite at Turhal in Turkey has been described by Maucher.[16]

The district lies about 180 kilometers from the Black Sea port of Samsun. The district is known for strong veins of stibnite with quartz, traversing schists. One vein cuts a mass of "diabase," which contains nickeliferous pyrrhotite. Inclusions of the nickel-bearing rock in the quartz-stibnite veins show gudmundite with stibnite, marcasite, pyrite, and bravoite. Maucher believes the gudmundite to have formed from iron extracted from the included iron bearing minerals, particularly bravoite.

Waldsassen.—Maucher mentions also, parenthetically, an occurrence of gudmundite at the Beyesland mine at Waldsassen, in the Upper Palatinate, Germany. "Here too Sb-bearing veins (boulangerite veins) meet with pyrite ores. In addition to gudmundite, bournonite and fahlerz are also formed." Whether the gudmundite mineralization is a late stage of the original pyritic mineralization or whether it is not connected genetically with the pyritic mineralization is not clear.

PARAGENETIC CONCLUSIONS.

The following generalizations seem proper for the seven European occurrences of gudmundite. The Turhal deposit is unique.

1. Gudmundite favors heavy sulphide deposits rich in iron.
2. In these deposits it belongs to a group of minor minerals later than the main sulphides.
3. Arsenic may be present as arsenopyrite in early main mineralization.
4. Lead sulphantimonides and fahlerz (usually tetrahedrite) accompany gudmundite.
5. Gudmundite occurring in massive sulphantimonides commonly shows extremely complex intergrowths with a number of other minerals. These relations are in part due to replacement and in part may be the result of interactions of early formed minerals under changing thermal conditions. Exsolution may play a part.

[16] Maucher, A: Über Gudmundite aus der Antimonitlagerstätte von Turhal (Türkei). Metallwissenschaft [Berlin], 17: 617–619, 1938.

6. Gudmundite also clearly forms directly from mineral depositing solution in well defined crystals.

7. During the gudmundite stage there is a tendency for the Sb: Pb ratio to decrease.

8. Although the early and major minerals of the deposits may be from intermediate to high temperature the episode of deposition gudmundite and associated minerals is one of much lower temperature perhaps even low temperature, ending by the deposition of the ruby silvers.

9. Gold values may be either high or negligible.

YELLOWKNIFE.

The main point of distinction of the gudmundite in the Yellowknife district is its lack of direct association with heavy sulphides, and its occurrence in quartz veins containing sparse metallic minerals. However, heavy sulphides formed at high temperature are known in the region, but these have not as yet been studied with sufficient care to give any information on the possible occurrence of gudmundite.

At Yellowknife, gudmundite is found in the same veins as Pb sulphantimonides, fahlerz, etc. commonly found elsewhere, but the gudmundite is not in definite intergrowths with these minerals. Höltmjarn and Yellowknife have in common the presence of high gold values. The minor Te at Yellowknife does not have its counterpart in Scandinavia.[17]

The greatest difference is the abundant quartz at Yellowknife. However, the general sequence of deposition of elements at Yellowknife has a strong similarity to Scandinavia. The Yellowknife sequence may be crudely summed up as follows:

Fe
As
Zn
Sb
Co
Cu
Te
Pb

[17] At Boliden tellurides are known but these appear to be restricted to the second and third periods of mineralization. Gudmundite is recorded only from the ore of the first period.

Gudmundite occurs earlier in the succession at Yellowknife than elsewhere. The reason of this may well be the greatly different relative concentration of the elements at Yellowknife whereas compared to the other localities (except Turhal) the solutions were rich in silicon and low in iron.

In conclusion it should be emphasized, as have earlier writers, that gudmundite is probably a much more common mineral than its few known occurrences would imply. It is to be sought in any antimony bearing suite of minerals, particularly if Pb sulph-antimonides are recognized. Its great similarity to arsenopyrite makes necessary the use of chemical means to determine the presence of Sb.

PRINCETON UNIVERSITY,
PRINCETON, N. J.,
Aug. 2, 1940.

GRAY QUARTZ BRECCIA ORE BODY OF THE HIGHLAND MINE, BUTTE, MONTANA.

R. C. NEWCOMB.

ABSTRACT.

The auriferous-quartz ore body of the Highland Mine is an open textured siliceous sponge-breccia. It occurs as a replacement of Cambrian dolomite along a subordinate bedding fault that follows the hanging wall of a major fault. The sponge structure is secondary, having arisen from the almost complete abstraction of sulphides, principally pyrite. Volumetric accommodation to the leaching was marked by the collapse of many primary ore structures and by prodigious slumping. Secondary silica now weakly cements the fragments. The leaching improved the grade of the ore by residual concentration.

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INTRODUCTION.

THE Highland Mine is located on the southeast rim of the Basin Creek drainage basin 19 miles south of Butte, Montana. The mine is one of the oldest in Montana; to 1940 it has produced about 30,000 ounces of gold.

The present operators are working a body of auriferous quartz, called the "gray quartz breccia," whose texture and aggregation are unique. A search of the literature reveals only one similar

occurrence—a quartz (and barite) sand below the gossan at Kyshtim,[1] in the Ural Mountains.

This paper is published by permission of the general manager of the Butte Highlands Mining Company. The observations were made during 1938 and 1939 while the writer was daily sampling the mine and devoting occasional periods to geological mapping. Some of the petrographic work was done by W. M. Felts.

Previous geological work consists of: a reconnaissance of the area by Winchell,[2] an unpublished thesis on the ore body above the 600 level by Veasey,[3] unpublished private reports by Hart,[4] and a reconnaissance mapping of the vicinity by Weed.[5]

GENERAL GEOLOGY.

The rocks occurring in the locality are:

Recent:	Alluvium		
Eocene:	Granodiorite of the Boulder batholith.		
Mesozoic?	Richmond[2] Gabbro, probably a sill, 200 feet thick, between Flathead and Hasmark.		
Cambrian:	Hasmark—dolomite	1800+	feet
	phyllite	200	feet
	dolomite	600	feet
	Flathead Quartzite.		

Winchell called the dolomite formation Gallatin formation, but it is believed to correspond more closely to the Hasmark[6] formation of the Philipsburg area. The dolomite is a buff, white, and gray medium grained brittle dolomitic marble, in which the bedding is generally indiscernible.

[1] Stickney, A. W.: The pyritic copper deposits of Kyshtim, Russia. ECON. GEOL., vol. 10, 1915.

[2] Winchell, A. N.: Mining districts of the Dillon Quadrangle, Montana and adjacent areas. U. S. Geol. Surv. Bull. 574, 1914.

[3] Veazey, Stockton, Jr.: Geology and ore deposits of the Butte Highlands gold mine. Thesis, Montana School of Mines, 1934.

[4] Hart, L. H.: Unpublished geological reports to Anaconda Copper Mining Co. and to Butte Highlands Mining Company, 1933–1936, Company's files.

[5] Weed, W. H.: Geology and ore deposits of the Butte District, Montana. U. S. Geol. Surv. Prof. Pap. 74, 1912.

[6] Emmons, W. H., and Calkins, F. C.: Geology and ore deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Surv. Prof. Pap. 78, 1913.

Physiographically, the ridge that includes Nevin Hill is considered the trace of the Oligocene "summit" peneplain.[7] Fifteen miles to the east, and eight miles to the west, Miocene "Bozeman Lake" beds occur partly filling great deep valleys.[5] A Tertiary

FIG. 1. View of Nevin Hill and vicinity as seen from the west.

FIG. 2. Typical gray quartz breccia. Sharp angularity of fragments indicates a non-attrition genesis.

FIG. 3. Unmined gray quartz lying loosely against hanging wall. Often neighboring fragments can be refitted together.

[7] Atwood, W. W.: The Physiographic conditions at Butte, Montana and Bingham Canyon, Utah when the copper ores in these districts were enriched. ECON. GEOL., XI: 708, 1916.

erosion surface, which Atwood [8] figures and describes as "intermediate or bench level southwest of Butte," extends to within 3 miles of the mine and lies at an elevation of 6400 feet, 1000 feet below the mine.

Near the mine the sharp eastern side of Basin Creek Valley is a second-cycle fault-line escarpment (Fig. 1). This north-south vertical (?) fault zone, where crosscut by the mine haulage adit,

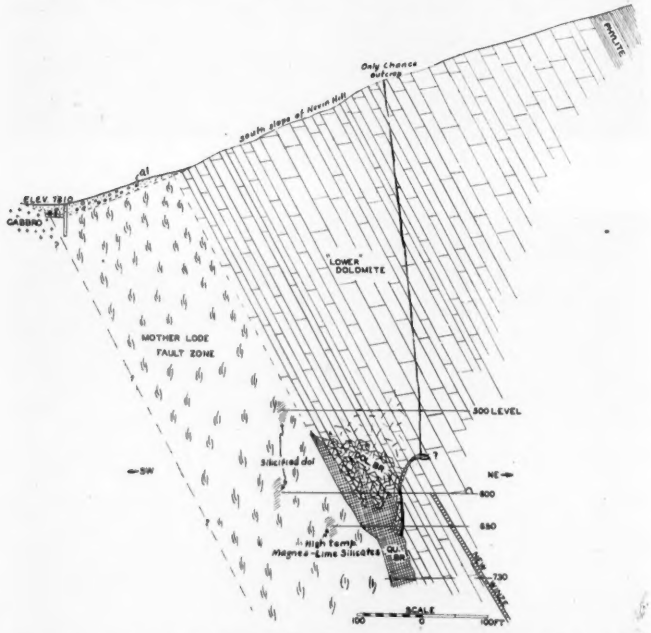

FIG. 4. Section (S30° W) through the mine workings showing the shape and structural relations of the gray quartz ore body.

consists of 150 feet of crushed rock. The "Mother Lode" fault, dipping 60° to the north, extends eastward from the Basin Creek fault. The junction of the two is 1600 feet south of the mine haulage adit. The Mother Lode fault trace passes eastward over

[8] Idem., Plate XXXVI, A and B.

the Continental Divide through the marked swale south of Nevin Hill.

Nevin Hill is made up of the Hasmark formation, which has a general north dip of 50°–70°. At the south foot of Nevin Hill the Mother Lode fault intersects the axial plane of a north-plunging anticlinal crossfold in the Hasmark dolomite. Down-

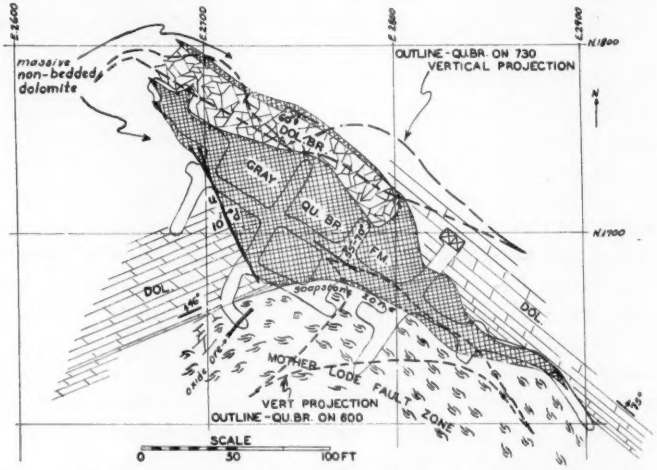

FIG. 5. Geological map of the 650 level showing relations of the gray quartz ore body.

ward along the projected dip of this intersection lies the gray quartz ore body, a vein replacement.

The main ore body terminates upward at 400 feet below the surface. Several small stringers diverge from the main body at the 600 level and outcrop near the crest of Nevin Hill. These stringers are essentially vertical but pursue a discontinuous and sometimes tortuous course. None of them average over 10 inches in width.

GRAY QUARTZ BRECCIA.

Host Rock Structure.—The plan of the ore body on three levels is shown in Fig. 5. On the 600 level it follows the bedding

and also follows a fault (hereafter called the "Parent" fault), which is accordant with the bedding of the east limb but which crosses the crest of the fold about at the axis. On the 650 level the ore principally follows the Parent fault with the bedding of the west limb being represented only by minor ore stringers. On the 730 level the ore body follows the Parent fault plane; although no bedding is evident, what are apparently two reflections of the bedding are shown by the southwestward trend of the medial constriction and by the abrupt southwestward turn of the vein near its west end.

This mineralized Parent fault was probably of small displacement. Beyond the eastern limit of the ore, above the 730 level, the Parent fault disappears into the Mother Lode fault zone; below the 730 it is occupied by an earlier high temperature pyrrhotitic amphibolite ore body. The western continuation of the Parent fault on the 600 level lies in a rehealed dolomite breccia zone, but on the 650 and 730 levels its western continuation was never recognized and it is definitely nonexistent on the 730 level. The inconstancy of the mineralized Parent fault is typical, as the observed faults of small displacement (including the mineralized one) are habitually short and of variable throw. In the surface workings, the displacement of any one fault can often be seen to transfer abruptly to another adjacent or intersecting fault. In every case where the direction of movement could be obtained, the subordinate faults in the dolomite are normal ones.

The parent opening for the quartz mineralization may be summarily described as: a steep, normal bedding fault, of small displacement, whose fracture plane and consequent mineralization are greatly complicated where the fault crossed the curved and broken strata at the axis of the anticlinal crossfold.

Vein Structure.—There was noted only one post-ore fault in which quartz breccia was involved. That one represented a 10-foot displacement of the ore body downward along its footwall. Absence of linear fractures within the quartz body doubtless is due to the character of the material, which yields by sagging, bulging, and running.

The brecciation of the quartz is uniformly prevalent from wall to wall except for a few hanging wall embayments wherein blocky, jointed "chalcedonic" quartz formation has not been brecciated. This blocky quartz carries pyrite irregularly in disseminations and anastomosing streaks.

Zones of equal-size particles, where they do exist, are generally shapeless. However, a weak linearity exists in some aggregations of coarse fragments; these coarse zones may be 5 feet wide and up to 30 or 40 feet long.

In places the breccia formation is a composite of rudely discordant indefinite strata formed by non-persistent bands of roughly even-size fragments (Fig. 2).

Walls.—The Parent fault zone, occupied by the ore body, parallels and partly follows the hanging wall of the Mother Lode fault zone. Hence, the footwall of the ore body is part of the altered zone of the Mother Lode fault and the hanging wall of the ore body is principally solid dolomite.

At any one place the footwall may be one or several of the many siliceous alterations of dolomite that make up the Mother Lode fault zone. Massive steatite soapstone is generally the footwall of the ore; commonly, it is an earthy alteration of dolomite that carries phlogopite mica in flakes and books up to 2 inches across.

The hanging wall is solid dolomite, except at the west end where a wedge of broken and jumbled dolomite lies between the main ore body and an hanging wall stringer (Figs. 5 and 8). Where this broken dolomite and the quartz breccia adjoin, the two are commonly interstratified in foreset bands that may be up to 6 inches thick. The interbedding of the two loose materials is interpreted as an alternate sloughing of the two formations into water-filled open cavities. One instance of such interbedded quartz and dolomite on the 800 level occurs at the debouchment of a circular, chimney-like hole, 4 feet in diameter, extending 15 feet upward into the solid hanging wall along a small oxide-quartz pipe.

On the dolomite hanging wall limonite forms a continuous crust 2 inches to 6 feet thick, and extends along joints a few feet

into the dolomite. But on the footwall this crust is weak and generally absent. Malachite may occur at the junction of the limonite with the dolomite wall. Locally where the hanging wall is nearly horizontal, the quartz fragments may be loosely in contact with it, or may lie even as much as six inches below it. Dolomite on the hanging wall is almost entirely unaltered; hence the absence of any transition zone, other than secondary limonite crust, is puzzling. The usual explanation [9] is that the siliceous solutions were highly viscous and could not penetrate the walls to effect a gradational zone. But here the solutions were of low viscosity as indicated by the thinness of the offshoot stringers. It is probable that slumping destroyed some contact gradation and makes the contact appear sharper than it was originally.

Near the hanging wall in the upper part of the ore body there occur many unaltered dolomite horses with crusted limonite about their embayed margins.

Physical Description.—The breccia is an aggregation of white, gray or black fragments that range in size from almost molecular (they show Brownian movement in index oils) to about 18 inches in diameter. The fragments are roughly of three types, which may occur in any proportions. One type is dense, micro-crystalline, waxy quartz whose color and luster depend upon the amount of liquid and gaseous inclusions; this quartz generally occurs as angular pieces ¼ to 3 inches in diameter. A second type is cellular, pumice-like, gray and white, fine grained quartz-sponge, having as much as 70 or 80 per cent porosity. Cell diameter averages about 1 mm., the volumetric ratio of cell to septa is about 1 : 1. Despite the fact that the septa rarely show negatives of the dissolved material, the sponge structure is believed to be all secondary; either the former pyrite was entirely anhedral or the septa were largely destroyed during and after the leaching. Fragments of the third type are angular white quartz powder ranging from .01 mm. diameter down to almost molecular size. This powder is secondary since it originated both as a residue after

[9] Lindgren, Waldemar: Mineral Deposits, McGraw-Hill Book Co., pp. 189–190, 1933.

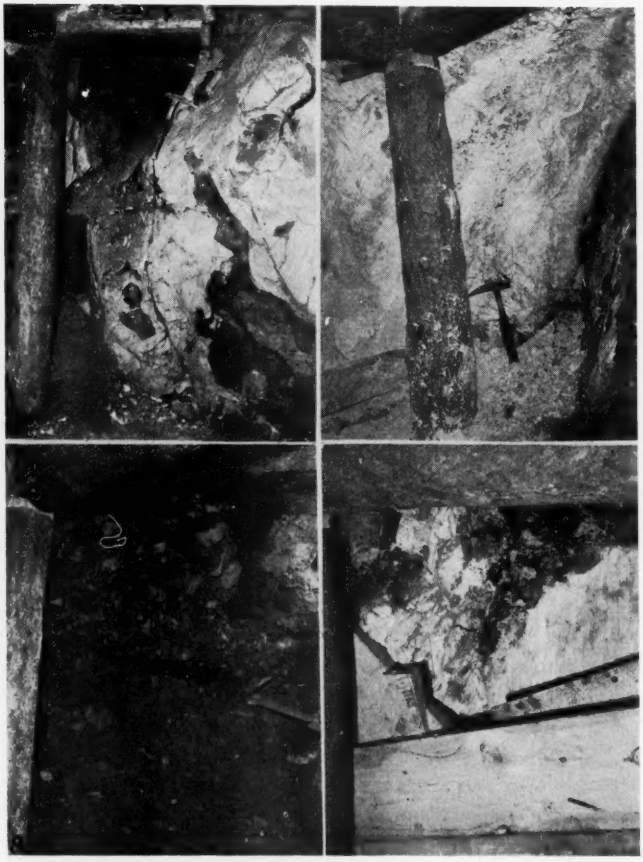

FIG. 6. Dolomite hanging wall. Coarse quartz shows above lagging. Crusted limonite remains in one embayment.

FIG. 7. Powder and sand phases of the gray quartz breccia on hanging wall which here has a reversed dip.

FIG. 8. Jumbled dolomite hanging wall in zone of hanging wall subsidence at west end of ore body. Quartz shows at upper right.

FIG. 9. Diversely oriented glide planes on talc intermixed with the gray quartz at the east end of the ore body.

the leaching of microscopic quartz-pyrite mixtures and as a result of attack on chalcedonic quartz along cracks.

Although any combination of the three types of fragments may be found, the breccia most commonly is an aggregation of angular, dark-gray fragments, ¼ to 1 inch in diameter, embedded in an equal amount of white and gray matrix of quartz grit and powder. The breccia formation becomes less porous and more coarse with depth.

Generally a small amount of supergene quartz "frost" acts as a friable cement, but even this may be missing. The weak cohesion of the aggregation is largely due to compaction, and consequently, is lacking in zones of equal-size fragments of the coarser sizes.

The most remarkable physical characteristic of the gray quartz is its porosity. The mined dry ore averages approximately 28 cubic feet per ton, which means a specific gravity of 1.14 and a porosity of 57 per cent. The ore formation in place has only slightly greater specific gravity. The porosity of the quartz breccia formation is due in minor part to drusy cavities up to 1 inch in diameter, in large part to interfragment voids, and to secondary sponge structure.

Mineralogy.—The gray quartz ore is entirely quartz except for a small amount of haphazard limonite stain, a localized intermixture of talc (after anthophyllite), and some relict pyrite. Minute quantities of galena and sphalerite with some chalcopyrite have been identified in mechanically concentrated samples from ore dressing tests.

Where relict pyrite occurs in blocky quartz no iron oxides, beyond a weak limonite stain, are associated with it even though the newly pitted borders of the blocks show that pyrite is being removed.

Quartz is of the alpha (−573° C.) modification.

Microscopic examination reveals four steps in vein mineral development; the two principal ones are hypogene and the two minor ones are supergene. First, "chalcedonic" (very fine grained) quartz replaced dolomite. Then, veinlets of fine grained quartz

accompanied by pyrite cut the early quartz. Next, a fine quartz powder, possibly produced by slightly alkaline solutions such as calcium-charged groundwater, developed along cracks in the chalcedonic quartz. Finally, secondary silica "frost" was deposited by groundwater.

No evidence of tellurium was seen, although there has been common report of the gold telluride in the Highland District.

Gold Occurrence.—Ore tenor is quite uniform and averages about .6 ounces ($21.00) per ton. Within the quartz ore body there have been found only two small zones that carried less than .2 ounces per ton; these zones were indistinguishable from the remainder of the breccia formation.

In general, the porous quartz is higher grade than the nonporous; however, exceptionally high grade zones occur in both. The pyritic quartz generally carries less gold per ton than does the brecciated pyrite-free quartz.

The silver-gold ratio is .04:1 gold. So small are the gold particles that they may be entirely invisible even in exceptionally rich, 20 ounce ore. The small size of the gold particles is further indicated by the fact that it is necessary to grind the ore to 80 per cent minus 200 mesh to free the gold for cyanidation.

Genetic Interpretation.—It is necessary to determine the genesis of this breccia both in order to direct search for similar bodies and also to interpret its puzzling texture. This study is concerned mostly with the genesis of the breccia because it is believed to be unusual and because its development destroyed many of the primary structures of the quartz.

The pertinent indications of the breccia's genesis are considered to be:

A. Mineralogical—

(1) the oxidation of the ore body,
(2) the presence of relict pyrite in disseminations and in anastomosing streaks in unbrecciated quartz within the hanging wall embayments,
(3) the absence of limonite from about relict pyrite,
(4) the localized occurrence of pyritic anthophyllite-quartz rock and a corresponding disintegration product of non-pyritic talc-quartz residue;

B. Textural—

(1) the sponge structure observed in large and small fragments,
(2) the angularity common to all fragments,
(3) the open texture of the breccia against the unaltered solid hanging wall;

C. Structural—

(1) the general wall to wall similarity of degree and type of brecciation and the commonness of all textures and aggregations therein,
(2) the existence of subvertical open cavities in the hanging wall,
(3) the local interstratification of loose hanging wall debris with quartz breccia ore,
(4) the localized presence of discontinuous and unoriented talc glide planes,
(5) the shearing and slickensiding of the footwall soapstone adjacent to the quartz ore body.

The stages in the development of the gray quartz breccia are interpreted to have been:

(1) After emplacement of the Boulder batholith, gold bearing siliceous solutions ascended via the Mother Lode fault into the broken ground at the axis of the cross fold. The quartz apparently emplaced itself in a compound veinwork of anastomosing quartz veins that excluded from within its general outer boundaries all host rock except a few blocky horses.

(2) Anhedral and subhedral pyrite with some chalcopyrite and a very little galena and sphalerite accompanied the second "surge" of silica. The replacement took place rapidly and completely so that the resulting ore consisted of an irregular intimate mixture of microscopic quartz and sulphide. Some linear zones were devoid of sulphides.

(3) The physiography of the region suggests that the ore body has been in the zone of descending groundwater since middle Tertiary time. As shown by the strong persistent flow of mine water and by the velocity (about 100 feet per day) with which surface floods reach the mine workings, the groundwater circulation is now quite active. Practically the same hydrologic conditions are believed to have prevailed since the carving of the great valleys of Divide and Silver Bow Creeks in mid-Tertiary time. Under the acid conditions that prevailed in the oxidizing vein, the pyrite went into solution as the sulphate and migrated downward with the

groundwater circulation. The resultant greater porosity accelerated groundwater passage. It is significant that the quartz breccia body is leached beyond the deepest level (800) opened to date, and the adjacent dense amphibolite ore body is mostly unoxidized on the 730 level. Some of the iron (and copper) sulphates came in contact with the dolomite wall and, under the neutralizing influence, precipitated to form a limonite crust. So complete was the abstraction of the pyrite that none now remains except in sheltered embayments along the hanging wall. Nothing indicates that any of the gold was leached.

Locke [10] has described the result of such pyritic leaching as:

> The extreme result of the removal of sulfides is the siliceous sponge found spottily developed in gossans. The sponge is made by the removal of pyrite, and sometimes of sphalerite. It carries cells, cubic or irregular, measuring as much as half a centimeter across and having septa which represent the former divisions between sulfide grains; it varies from a mere pepper of cavities through gangue, in which the walls exceed the cells in diameter, to a true sponge, like pumice, so light that it floats on water and so friable that it easily crushes down into sand. . . . Often blebs of the sponge are enclosed in bodies of quartz strong enough to protect them from crushing.

(4) The resultant quartz sponge in many places collapsed and was crushed. In places where pyrite had greatly predominated only a residue of grit and powder remained. The great decrease in volume caused slumping and settling, so that even the chalcedonic streaks, originally free of sulphides, fell apart and lost their general continuity. In places temporary large shrinkage voids permitted ore to run much as rock backfill runs into a filling stope. Much of the slack space was apparently taken up by the crowding of the plastic footwall. The hanging wall remained firm except at its northwest end where it was free to follow the ore downward. The present mining operations find the volumetric adjustment largely completed as evidenced by the prevalent weak cementation, but compaction and readjustment are still going on as shown in some places by open spaces along the hanging wall and by exceptionally open texture of the fractured chalcedonic quartz.

[10] Locke, Augustus: Leached Outcrops as Guides to Copper Ore. The Williams and Wilkins Co., pp. 75–76, 1926.

SOME MINING CONSIDERATIONS.

Mine openings in the quartz breccia are now all made by pick except for very infrequent well cemented streaks that necessitate jack hammer plugging. All openings must be promptly and securely timbered. The loose formation "gives" under the pressure of a block and wedge; hence, really tight timbering is impossible. The formation usually causes the timber to "take weight" but its weight practically never breaks timber. The plastic footwall slowly crowds the mine openings horizontally with a force sufficient to break heavy timber and in time to close all slack space in gobbed stopes or cribbed bulkhead. The bulkiness of the breccia formation materially raises mining costs; the overall mine extraction during 1938 being about one ton per man-day while prospecting the ore body's extremities and exploiting the ore body on a 60 ton per day basis.

The gray quartz ore is so friable that specimens will not stand up long. Soon after the ore body has been mined, except for the written record, a unique ore may be forever lost.

BUTTE, MONTANA,
Oct. 16, 1940.

MECHANICAL POLISHING WITH A FILM OF ABRASIVE.

J. OSBORN FULLER.

ABSTRACT.

An improved polishing method utilizing a film of abrasive on metal laps is described. The abrasive film provides a greater number of active cutting particles than a fixed abrasive and does not give a surface with scratches and waviness such as is produced by a freely rolling abrasive. With this technique, a mounted surface can be ground and polished in less than an hour. Only two abrasives are used and the resulting surface is free from scratches and relief. The principle of the abrasive film is discussed. Problems concerning laps and abrasives are considered, and a detailed outline of the procedure is given.

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INTRODUCTION.

EXPERIENCE in polishing with the Graton-Vanderwilt type of machine has resulted in the development of a technique that in 10 to 60 minutes gives results comparable to those formerly described in the literature as taking 3 to 12 hours. The method is of such nature that it is not limited to this particular machine but is applicable to any machine using metal laps. Due to extensive

use of polished surfaces of metallic minerals in microscopic study it is believed that the improvement warrants record.

Experiments designed to reduce the operating time and yet maintain the perfect polish achieved by the Vanderwilt method [1] have led to wider use of the "abrasive film." The principal point of departure from earlier methods is that a film of abrasive of recognizable thickness is used on the metallic laps instead of fixed or rolling abrasive.[2]

In general the minerals most exposed to attack by the abrasives are polished quickly. In polishing on cloth laps the soft minerals of a mixed ore are polished quickly while on metal laps the soft minerals are protected by relief and the hard minerals polish more readily. The chief time consuming factor is the reduction of relief between minerals of different hardness.

The original Vanderwilt method of using a fixed abrasive in metal laps practically eliminates relief but in order to keep the abrasive fixed, such a small quantity of abrasive is used that the cutting power is reduced greatly and the polishing time is extended. The abrasive film increases the amount of active abrasive and at the same time keeps the abrasive from rolling freely thus eliminating scratches and relief.

PRINCIPLES.

Rolling and Fixed Abrasives.—The distinction between rolling and fixed abrasive is a useful one as shown by the progress in polishing that has resulted from Vanderwilt's work. "Fixed" and "rolling," however, are only relative terms. Abrasive impregnated in the soft metal laps used by Vanderwilt is fixed in the sense that it cannot be removed by washing. If a lap is heavily charged with abrasive, washed clean, and then run with a specimen, a thin coat of abrasive covers the specimen. Apparently the greater friction of running the specimen compared with washing or even scrubbing the lap is sufficient to loosen some of the

[1] Vanderwilt, J. W.: Some improvements in the polishing of ores. ECON. GEOL., 23: 292–316, 1928.

[2] This is the procedure recommended by the Mica Instrument Co., Cambridge, Mass., makers of the new type Vanderwilt machine.

abrasive and to change it from a fixed to a rolling state. Thus, in the course of ordinary polishing a fixed abrasive may roll or a rolling abrasive may become temporarily fixed. Vanderwilt recognizes this former possibility and he states, " When polishing with metal laps it was found necessary, in the final stages of polishing, to avoid an excess of abrasive and lubricant to prevent rolling of grains." [3]

If much abrasive is used, all of it is not solidly embedded, and some works free to produce scratches and relief. Lubricants aid the loosening. The problem in the Vanderwilt method is to reduce the quantity of abrasive to such an extent that every particle is embedded sufficiently so that the slight amount of lubricant necessary to reduce friction and to keep the specimen from plucking is not enough to loosen the abrasive. When this balance is achieved, the abrasive is reduced to such a small quantity that its grinding or polishing power is slight, and consequently a long time is required to polish a surface. With abrasive so thoroughly embedded a slight amount of lubricant greatly cushions the grinding or polishing action. This cushioning effect is made apparent by using pure oil and then diluting it successively with greater quantities of kerosene. When a heavy lubricant such as Nujol or mineral oil is used alone the abrading action of fine abrasive is almost negligible. The abrasion increases with the increased percentage of kerosene and is best with pure kerosene. The disadvantage in using pure kerosene is that it evaporates quickly and leaves the lap so dry that grains are apt to be plucked.

Abrasive Film.—Experiments prove that the type of movement and abrasive action of individual particles in an abrasive film lie between the conditions of the fixed abrasive and the freely rolling abrasive. In the film each particle is kept from rapid rolling by the adjacent particles and by adhesion of the lubricant and particles. Some rolling of particles probably occurs but sharp edges are prevented from digging deeply into the soft minerals of the specimen by the cushioning effect of other particles and of the oil. As with a fixed abrasive, each particle exposes to the specimen a small cut-

[3] *Op. cit.*, p. 301.

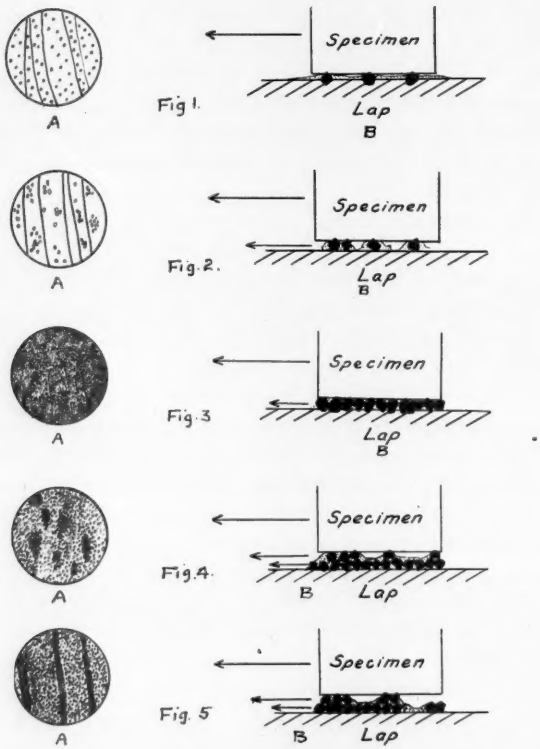

FIG. 1. *A*. Distribution of fixed abrasive (MgO) on lead lap as seen with a microscope. Note few particles to abrade. × 175. *B*. Fixed abrasive impregnated in lead lap. Only part of diameter of particle can abrade. Lubricant (dots) acts as cushion lessening abrasion.

FIG. 2. *A*. Irregular distribution of rolling abrasive (305) on cast iron lap as seen with microscope. × 175. *B*. Rolling abrasive on metal lap. Arrows indicate relative amounts of movement. Whole diameter of particle can abrade.

FIG. 3. *A*. Regular distribution of abrasive of the abrasive film on the metal lap. Note abundance of possible cutting surfaces. × 175. *B*. Abrasive film on metal lap. Only top edges of particles capable of abrad-

ting surface which is considerably less than the size of the particle, although roughly proportional to its size. Thus, coarse abrasive particles have more irregular cutting edges than finer ones, and the cutting on the specimen is rougher. In contrast, however, with the fixed abrasive the greater quantity of abrading particles in an abrasive film increases the speed of abrasion. Figures 1, 2 and 3 show some of these relations.

Experience shows that there are two things that destroy the perfect polishing effect of the abrasive film. One is too much abrasive on the lap; the other is excessive lubricant. If too much abrasive is spread on the lap, the specimen and bakelite become scratched and relief develops. Apparently increase of abrasive beyond a certain point results in free rolling of some of the abrasive which readily abrades and scratches softer minerals. Microscopic examination of the distribution of abrasive on a lap carrying excessive abrasive shows that the abrasive is irregularly concentrated. Apparently little piles of abrasive develop and with movement of the lap some free rolling occurs (Fig. 4).

Excessive lubricant similarly destroys the polishing effect by promoting a local rolling of abrasive. Microscopic examination of a lap shows black streaks or ridges of concentrated abrasive separated by greyer and thinner streaks where the metal of the lap is visible (Fig. 5). Probably there is rolling of abrasive from the ridges as well as end over end rolling in the troughs

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ing specimens principally because of cushioning effects of adjacent particles and lubricant (dots).

FIG. 4. *A.* Irregular distribution of abrasive on a lap with too much abrasive. Darker areas appear to be piles of abrasive. × 175. *B.* Cause for rolling abrasive when the lap has too much abrasive. Length of arrows indicate relative amounts of movement. Relief as well as the typical scratches caused by rolling abrasive develop.

FIG. 5. *A.* Microscopic view of lap which had excessive lubricant. The distribution indicates ridges of abrasive between valleys covered by a thin coat of abrasive through which the metal lap can be seen. *B.* How excessive lubricant probably causes rolling abrasive. Abrasive probably rolls from ridges and rolls freely in troughs where there is not complete cushioning by other particles.

where the cushioning effect of the adjacent particles is not complete. The abrasive seems to be in suspension in the lubricant rather than in the form of a mat or film bound together by the liquid.

EQUIPMENT.

Laps.—This procedure can be used with any equipment using metal laps. At Columbia University a Graton-Vanderwilt machine [4] is used to grind and polish the mounted specimen. The earlier machines had eccentric shafts so that the mount passed over the entire lap surface and supposedly kept it true. Experience proved that the specimen and bakelite of the mount were of enough difference in hardness to cause differential wear of the laps producing a dished surface. This was corrected in a newer and faster type of machine developed in by the Mann Instrument Co. of Cambridge, Mass. Murdock [5] made a similar correction for inexpensive machines in which the mount successively overlaps the outer and inner edges by approximately ½ in., making the harder specimen run over the whole surface of the lap. This adjustment corrects much of the difficulty of depressed laps. J. A. Dunn [6] has successfully decreased wear of lap by spacing the grooves farther apart at the center than at the edge. The newer models of the Graton-Vanderwilt machine [7] use a ring-shaped lap which obviates dishing of the laps.

Abrasives.—The writer feels that the important factors in polishing are the state of the abrasive, *i.e.*, fixed, rolling or film; and the gradual decrease in size of abrasives. Apparently there is no upper limit of particle size if the gradations to finer particles are not too abrupt. Vanderwilt believed that abrasives coarser than 0.01 mm. produced subsurface fracturing, which could not

[4] Graton, L. C.: Technique of mineralography at Harvard. Am. Min., 22: 493, fig. 1, 1937.

[5] Murdock, Joseph: A polishing apparatus for ore minerals. Econ. Geol., 33: 542–553, 1933.

[6] Dunn, J. A.: Polished and thin section technique in the laboratory of the Geological Survey of India. Records, Geol. Surv. of India, 72, pt. 2: 217, 1937.

[7] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914: 35–36, 1940.

be eliminated in the later stages. He illustrates a surface in which flaws produced by 0.015 mm. alundum have not been removed completely after 3 hours of polishing with 0.0025 mm. alundum.[8] The size difference is 0.0125 mm.; a drop from a particle 6 times as large. This is too abrupt a change from a relatively coarse to a fine particle. In his original procedure the step taking the longest time (2 to 5 hours), has the largest difference in abrasives (¼ the size of the previous stage). The modified procedure now used at Harvard[9] has eliminated the abrupt changes in size with consequent reduction in time although no coarse abrasives are used.

Murdock and the writer use abrasives many times those prescribed by Vanderwilt and also those used at present at Harvard. The successive steps, however, are well graded and the use of coarse abrasives as Murdock states, "does not seem to produce serious shattering of the brittle minerals, nor to lengthen unduly the time necessary for the complete polishing."[10]

The abrasives used at Columbia are as follows:

1. Rolling 100 carborundum on cast iron. ..... 0.18 mm.
2. Rolling FFF carborundum on steel. ..... 0.018 mm.
3. Rolling 303½ optical emery on copper. ..... 0.01 mm.
4. Abrasive film 305 optical emery on lead. ..... 0.004 mm.
5. Abrasive film MgO (Merck & Co.) on lead. ..... 0.002 mm.

With the abrasive film coarser abrasives can be used in the final polishing than in other methods and this eliminates the necessity of elutriating abrasives.

PROCEDURE.

Preparation.—A sawed or chiseled chip is shaped to the proper size for mounting in about 4 minutes, using the abrasives and laps listed above in the first 3 steps. The edges are ground smooth in order to reduce plucking in the polishing stage to a minimum and

[8] *Op. cit.*, 304.

[9] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914: 32–37, 1940.

[10] Murdock, Joseph: A polishing apparatus for ore minerals. ECON. GEOL., 33: 551, 1938.

thereby eliminate the necessity of impregnating the average specimen. Friable specimens are impregnated with bakelite as described in the literature.[11-14] The chip is mounted using a hydraulic press at a temperature of 140° C. for 8 minutes. Various methods of mounting have been described in the literature.[15-21]

In both the grinding and polishing stages the preparation of the abrasive paste and its application is essentially the same. The lubricant (equal proportions of mineral oil or Nujol and kerosene), is mixed to make a paste which, when smoothed with a spatula, forms an even but slightly pitted surface. The paste is spread on the lap with the forefinger.

Grinding Specimens.—When grinding with a clean cast iron lap several ¼ in. balls of 305 abrasive paste will be necessary to cover the lap. This first covering will invariably be too fluid to give the best results. However, a more plastic paste cakes and is difficult to spread over the lap. It is much simpler to apply paste of the described consistency and then to run a steel block on the lap until the film is in the proper condition. Running the block spreads and partially dries the paste. When fluid the paste has a

[11] Ross, C. S.: A method of preparing thin sections of friable rock. Am. Jour. Sci. 5th ser., 7: 483–485, 1924.

[12] Ross, C. S.: Methods of preparation of sedimentary materials for study. ECON. GEOL., 21: 464, 1926.

[13] Short, M. N.: Preparation of polished sections of ores. ECON. GEOL., 21: 552, 1926.

[14] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914: 30–32, 1940.

[15] Bird, P. H.: Mounting concentrates and tailings for microscopic study. Eng. & Min. Jour. 136, No. 5, May, 1935.

[16] Dunn, J. A.: Polished and thin section technique in the laboratory of the Geological Survey of India. Records, Geol. Surv. of India, 72, pt. 2: 207–226, 1937.

[17] Fuller, H. C.: Mounting polished surfaces in bakelite. ECON. GEOL., 28: 393–395, 1933.

[18] Krieger, Philip, and Bird, P. H.: Mounting polished surfaces in bakelite. ECON. GEOL., 27: 675–678, 1932.

[19] Myers, P. B.: Talc as lubricator for polished surfaces mounted in bakelite. ECON. GEOL., 29: 502, 1934.

[20] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 914: 8–42, 1940.

[21] Stillwell, F. L.: Bakelite press for mounting mineral grains and ores. Australasian Instit. Min. and Met. Proc. N. S. No. 90: 237, 1933.

velvety black luster. If the specimen is run while the lap is in this condition, it will grind down readily, but long deep scratches will develop both in the specimen and bakelite. Apparently the lustrous black coat is not firm enough to form an abrasive film and rolling particles cause scratches. After running the lap with the block for several minutes, the paste will dry slightly and the luster will disappear. The lap coating will be a dull grey with a dry appearance, but it is still a paste as may be felt by rubbing the finger over the lap. An abrasive film now covers the lap and the specimen may be substituted for the steel block. The specimen is ground from 2 to 5 minutes, depending on the character of the specimen after mounting. When the shiny luster of the bakelite has been ground down so that there is about ⅛ in. border of dull bakelite all around the chip, the specimen is ready for polishing. Microscopic examination of the chip at this stage shows a dull surface, in which harder minerals like pyrite have a high burnish and show fine scratches. Softer minerals show fine pits, but there are no deep scratches. Deep scratches are more difficult to remove in the polishing stage than these pits, and if present, indicate that the lap probably was too wet.

If the original abrasive applied was insufficient or if the lap has been run too long without the addition of abrasive, the coat will wear thin and the metal will become exposed. The abrasive forms almost a powder which tends to collect in small cakes and exposes more and more of the bright metal lap. Specimens run on a lap in this condition will have a better polish on harder minerals, but these minerals will also have long deep scratches, which are difficult to remove in the polishing stage. The above procedure is a grinding stage, and no attempt should be made to polish any of the minerals with such coarse abrasive. The scratches produced do not justify the polish gained. Only one specimen is run at a time on the cast iron lap because it is much easier to keep the lap in proper condition. If, unwittingly, relief develops because the abrasive is too fluid it is necessary to run the specimen for an additional 5 minutes on the cast iron lap. Relief not removed on the cast iron lap will more than double the time required to polish on the lead lap.

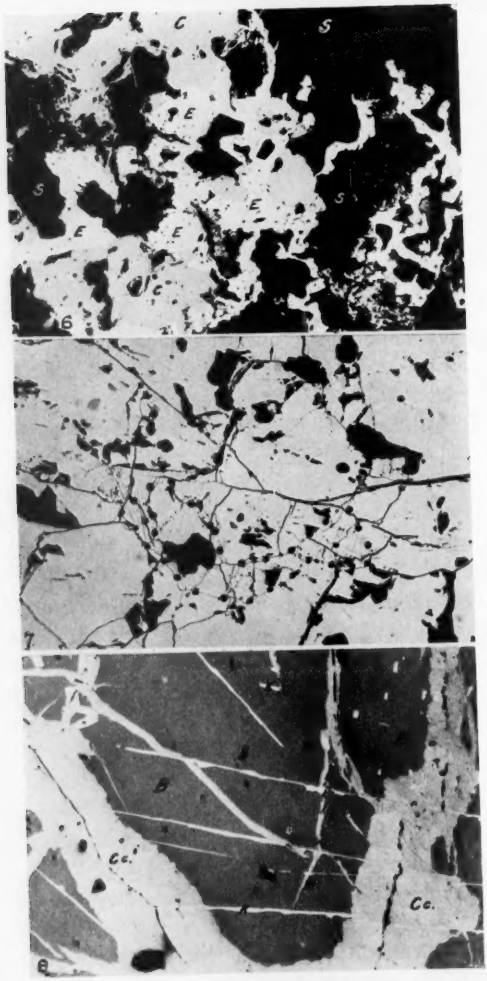

FIG. 6. Ore from Tayolita, Durango, Mexico, showing polish on minerals of varying hardness using the abrasive film. Sphalerite, S.; chalcopyrite, C.; electrum, E. Oil immersion × 100.

FIG. 7. Ore from Sinaloa, Mex., showing polish of hard minerals with

Normally, specimens are taken in groups of 12 to 20. Each specimen is run from 2 to 5 minutes, and then a slight amount of abrasive is added and the next specimen is run. The amount of abrasive depends on the condition of the lap, but it is never more than a ⅛-in. pellet, and usually is about half this amount. The cast iron lap is put away without cleaning because the most difficult part of this operation is getting the lap in shape. If it is put away without cleaning, a ⅛-in. application of abrasive at the beginning of the next run will be sufficient to get it back in shape.

Polishing Specimens.—In polishing on the lead lap with magnesium oxide the same general technique and paste mixture are used as with the cast iron lap and emery. Just enough lubricant is added to moisten the abrasive. The paste looks about the consistency of whipped cream that has been whipped a little too long to be perfectly smooth. When rubbed with a spatula this paste forms an even layer with slight pits. If the paste is too wet relief and scratches result and it is best to reduce the relief on the cast iron lap and then proceed again with the lead lap and a drier paste. Several minutes on a soupy lap will develop relief which will take several hours to remove with the MgO paste on the lead lap but which may be removed on the cast iron lap in about 5 minutes.

To build an abrasive layer on the lap a ¼-in. pellet of paste is spread with the forefinger and the steel block is run to distribute the paste. When the steel block shows a very thin film of abrasive with criss-cross lines about ⅛ in. to ¼ in. broad the lap has the proper film. If the abrasive is too thick, it will gather on the edges and leave a thick mat on the face of the block with or without criss-cross lines. If this happens, the lap surface should be wiped with cleaning tissue and the block run again until a thin film of criss-cross lines appear.

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abrasive film. Main mass is niccolite containing small rectangular inclusions of maucherite. The dots outline a cobalt-nickel arsenide, probably gersdorfite. Oil immersion × 100.

FIG. 8. Photomicrograph of ore showing chalcocite polished by film technique. Chalcocite, Cc.; bornite, B.; klaprothite, K.; as long bladed or rectangular inclusions. × 140.

If there is no visible paste on the steel block when it is removed, the lap lacks abrasive or is too dry. Usually the latter is true, for the tendency is to get too much abrasive rather than too little. Under these conditions adding a little more abrasive will usually solve the difficulty. Some surfaces appear to polish more quickly when the lap is dry. If, however, specimens are run long with the lap in this state, plucking almost invariably results, especially in small patches of quartz. With a dry lap, long gashes develop in galena, which are difficult to remove.

When the criss-cross pattern is visible, the steel block is removed and 3 specimens may be substituted. These specimens should be examined every 4 or 5 minutes to make sure that the criss-cross pattern is present on the face of the specimen and to observe the polishing under the microscope. Some specimens that contain no hard minerals polish in a few minutes. Even specimens containing minerals with considerable difference in hardness can usually be polished in at least 20 minutes if a good plane surface is obtained at the start. New specimens are substituted as fast as the old are finished. Abrasive in 1/64-in. balls, is added every 2 to 5 minutes to retain the criss-cross pattern. Occasionally when specimens do not contain any soft minerals, they are run drier to speed polishing.

Specimens should be examined frequently. In spite of the use of a machine, polishing is still an art. Each specimen has its own idiosyncrasies and must be treated as a separate case. With a little experience 20 to 40 mounts may be ground and polished in a day. Only a few trials will be necessary to learn to polish minerals harder than chalcopyrite but to learn to polish softer minerals a certain amount of skill must be acquired (Figs. 6–8).

SUMMARY OF PROCEDURE.

1. Chip cut and shaped with 100, FFF carborundum, and 303½ optical emery successively, using 2 cast iron laps and a grooved copper lap in the order named. Edges should be ground smooth.

2. Chip impregnated if necessary and then mounted in bakelite.

3. Specimen ground on grooved cast iron lap with a film of 305 emery for 2 to 5 minutes.

4. Three specimens polished at a time on a grooved lead lap with a film of MgO. Polishing takes from 2 to 20 minutes depending on the minerals present.

ACKNOWLEDGMENTS.

This paper presents the technique of polishing developed while the writer was working as an assistant to the late Dr. Philip Krieger at Columbia University from 1937 to 1939. The writer gratefully acknowledges suggestions on procedure and criticism of the manuscript made by Dr. Krieger. The photographs were taken by Dr. Krieger. Supplementary work has been preformed following suggestions made by Dr. P. F. Kerr of Columbia University who also has criticized the manuscript. Dr. A. F. Hagner of the University of Wyoming has offered criticism and suggestions. E. L. Evans, who followed the writer as assistant in the laboratory of Economic Geology at Columbia University, obtained similar results using this method.

MOUNT UNION COLLEGE,
ALLIANCE, OHIO,
Sept. 15, 1940.

DISCUSSION AND COMMUNICATIONS

NATURE OF THE ORE-FORMING FLUID.

Sir: In view of the tacit assumption by most geologists that ore-forming fluids are predominantly hydrothermal solutions, it may be as well to direct attention towards certain shortcomings of such media as important ore-carriers, let alone as agents of ore-deposition. The modern disregard of the physical, chemical and geological weaknesses inherent in a hydrothermal origin for most ores is reflected in the following three statements from Prof. Graton's recent paper:[1]

> There is agreement by all that ores of the broad family here considered and *in the condition known to us* are the work of hot liquid solutions, and are thus hydrothermal in the strict sense (p. 212). . . .
>
> we find both Ross and Schaller definitely convinced that the *dominant* reagent involved in hypogene ore formation in the one case and in the pegmatite modifications in the other case is a hydrothermal liquid solution (pp. 303, 304).
>
> since Bowen, Fenner and Ross agree that a hot liquid was the agent that caused the actual ores with which their study is concerned, we seem to be justified in applying, without any qualification, the designation *hydrothermal* to this great family of ores reaching from pyrometasomatic and hypothermal to epithermal and telethermal (p. 350).

Graton's definition of hydrothermal as a "hot watery *liquid*" (p. 206) follows that of Lindgren,[2] and remains as vague as it is incomplete, since "hot" and "watery" are but comparative terms, and "liquid" is not implicit in the adjective hydrothermal, except in so far as it rests upon the wholly arbitrary usage of Prof. Graton and others.

[1] Graton, L. C.: Nature of the ore-forming fluid. ECON. GEOL., 35: 197–358, 1940. Supp. to no. 2.

[2] Lindgren, Waldemar: Mineral Deposits, 3rd Edit., 1928, p. 143: The vein-forming solutions were probably liquid from the start, and often highly concentrated. They contained water as the principal constituent and were at all times in a mobile non-viscous condition.

Doubtless some deposits may be hydrothermal in Prof. Graton's "strict" sense, but by far the greater range shows undeniably greater affinities with "normal" pegmatite than with the hot spring residues, that have hitherto been used as a basis for the explanation of most mineralizing reactions.

One is entitled to ask:

1. What differences exist between the quartz of igneous rocks and of pegmatites, and that of the hypothermal ore veins, which would prove that the former crystallized from a magma and that the latter was deposited from a solute consisting predominantly of water?

2. A similar query is in order regarding those other minerals common to the magmatic stage in pegmatites and to the hypothermal veins, *e.g.* tourmaline and albite; also those of magmatic segregations such as the common sulphides.

3. In view of the important work of R. E. Gibson[3] on the elevation of the inversion temperature of quartz with increased pressure, and the discovery by V. B. Meen[4] of high-quartz in certain of the Canadian hypothermal veins, are we still to accept Lindgren's estimate of the temperature ranges of deposition of the various classes of deposits commonly called hydrothermal, without making necessary adjustments dependent upon the depth at which mineralization took place?

4. How can high-quartz be deposited at a temperature above 832° C. (at a depth of 30 km.) from a solution that ceases to be liquid several hundred degrees below that temperature?

5. Relying upon the solubility figure for silica in water at 335° C. determined by Hitchen[5] to be 0.21 parts of silica in 100 parts of water at a pressure of approximately 136 atmospheres, it may be asked whether the quantity of water required to hold in solu-

[3] Gibson, R. E.: The influence of pressure on the high-low inversion of quartz. Geophys. Lab. Pap. No. 663. (Reprinted from Jour. Phys. Chem., 32: 1197–1205 and 1206–1210, 1928.)

[4] Meen, V. B.: The temperature of formation of quartz and some associated minerals. Univ. of Toronto Studies, Geol. Ser. No. 38, pp. 61–68, 1935.

[5] Hitchen, C. Stansfield: A method for the experimental investigation of hydrothermal solutions, with notes on its application to the solubility of silica. Trans. Inst. Min. Met., 44: 277, 1935.

tion the amount of quartz introduced in the vicinity of the major hypothermal ore-bearing regions of the world is not equally unreasonable as that cited by Graton for the amount of gas involved in the chlorine transfer of iron at Cerro de Pasco?

6. According to a calculation by H. C. Boydell,[6] mineralizing solutions in a given case could lose less than 2° C. of their temperature in 5,000 feet of ascent along a vein zone. From Hitchen's experiments it can be found that the difference in silica solubility over a range of 2° C. at 335° C. is less than 0.003 parts of silica in 100 parts of water. Thus, each ton of quartz deposited *per foot of depth* would require the circulation through the vein zone of almost *170 million tons* of hydrothermal solution. In the case of a typical mine milling 1,000 tons daily, the amount of solution thus presumed to have been engaged in the deposition process of its normal ore reserve can be multiplied appropriately to give a figure of *170 billion tons,* or an even more untenable figure than that of Graton in the Cerro de Pasco case.

7. How can a magma yield "aqueous solutions rich in silica"[7] in view of Hitchen's determination of the low solubility of that substance in water?

8. Hitchen's determinations show that the solubility of silica in alkaline solutions decreases with rising temperatures; would not such solutions tend to rob the wall-rocks of quartz as they attained cooler horizons in the earth's crust?

9. What happens to Graton's "special ore fluid" if it finds no avenue of release from the magma chamber when once it has separated, by whatever process, from the main body of the magma?

10. What are the solid products of solutions derived from the magma when the latter is tapped slightly in advance of or during the separation of the supposed "special ore-forming fluid"?

11. What product appears when the supposed immiscible liquids within the magma are tapped simultaneously, and what is

[6] Boydell, H. C.: Temperature of formation of an epi-thermal ore deposit. Trans. Inst. Min. Met., 41: 499, 1932.

[7] Lindgren, Waldemar: *op. cit.*, p. 125.

to prevent both such liquids becoming channelized in the same vein system?

12. What happens to the vast quantities of water used in mineral transport under a hydrothermal system when the solutions are unable to reach the surface after depositing the bulk of their mineral content?

13. Would not hydrothermal solutions containing the amount of carbon dioxide essential to the formation of the carbonates be competent to decompose pyrite as soon as it had been formed, even in greater degree than this mineral undergoes alteration by surface waters?

14. Would not aqueous carbonated mineralizing solutions effect kaolinization of the wall-rock feldspars in the same manner that similar solutions of surface origin give rise to china-clay, yielding a totally different wall-rock alteration from that usually described as hydrothermal.

The entire absence of facts suggesting any condition of immiscibility within the magma from which the "hydrothermal" deposits are derived, and the lack of an abrupt change in the differentiation processes of the magma sufficient to account for the sudden production of hydrothermal solutions in adequate quantity at the end of the pegmatitic stage, render it vitally necessary to consider the products obtainable from the magma, should the latter be tapped at any given moment throughout the time-range of its existence.

It is suggested that the magmatic stage, in the formation of the quantitatively minor products of the magma, persists farther than the stage of production of "normal" pegmatite; in fact, it may persist to the leptothermal stage of ore-deposition, or close to the limits at which depositional banding of the quartz, and residual open-space within the veins (both taken to be indicative of crystallization from aqueous solution), become apparent.

The work of Gibson, previously mentioned, in conjunction with the known facts regarding the upper limit of quartz crystallization, bring the limiting temperatures for the formation of high-quartz, and permit some low-quartz to be formed, well within the

magmatic range of temperature and at reasonable depth, and tend to show that the concept of ore-magmas is as tenable a theory as any yet evolved in explanation of the processes of emplacement of such magmatic derivatives.

To avoid confusion, it is proposed to limit the term magma to the fluid within the magma chamber and its major embayments or apophyses, and to substitute the term *silicothermal solution* for such portions as are drawn off along dike-fissures and vein-zones to form the pegmatites and certain ore-deposits.

When, during the course of progress towards the surface, the bulk of the silica composing a silicothermal solution has been deposited, and conditions have been attained at which the water present assumes a liquid state, then only do the hydrothermal processes become active in the production of some of the lepto-thermal deposits, as well as those classified as epithermal and telethermal.

Such a theory as that proposed would:

1. Reconcile the common characteristics of the quartz of the igneous rocks, pegmatites, and ore-deposits of hypothermal and mesothermal character, by contrast with the banded variety of the lower temperature stages.

2. Account for the contrast between the compact vein-filling of the higher-temperature "hydrothermal" deposits with the drusy development of the lower-temperature types.

3. Yield a single deposition process for the sulphides found in both the magmatic segregations and many veins of the higher temperature category, and for the tourmaline common to igneous rocks, pegmatites, and many of the hypothermal veins.

4. Support a broader temperature range of ore-deposition consistent with the depth-range apparent for many ore-deposits whose general characters persist with little change for many thousands of feet vertically.

5. Clarify the position with regard to the occurrence of high-quartz in some hypothermal veins and in numerous pegmatites.

6. Obviate the practical difficulties involved in the transport of large quantities of silica in an aqueous solution.

7. Explain the usual graduated suite of magmatic derivatives dependent upon the tapping of the magma chamber at successively later stages throughout the differentiation process.

8. Conform with the known field-facts of geology in all respects connected with ore-deposits in general and their associated phenomena such as wall-rock alteration.

W. JAMES BICHAN.

SIGMA MINES, QUEBEC,
July 15, 1940.

ALBITE AND GOLD.

Sir: In Mr. David Gallagher's article on "Albite and Gold"[1] there is abundant information relative to the existence of albite in the genetically connected igneous rocks and also as a secondary or introduced mineral in the hydrothermally altered wall rocks of the veins. The evidence regarding its occurrence as an actual vein mineral, however, is less clear, and in this role it would appear to be at most a mere sparse accessory mineral as at the San Antonio Mine in Manitoba.

Within the last four years, however, two instances have come to my attention in which albite is conclusively the dominant gangue mineral in a gold vein.

The first of these is at the De Santis Gold Mine near Timmins, Ontario. In this mine albite occurs both on the 325 and 450 foot levels, but its characteristics are better shown on the latter. This occurrence, which is principally composed of albite, also carries considerable quartz in the form of stringers, and some pyrite together with gold, was regarded by the mine management as a mineralized albitite dike.

I (who was examining the mine at the time) held a contrary opinion, and considered the albite as an essential part of the vein formation, my reason for this belief being, that it pinches and swells along the course of the level, is intimately associated with the adjoining hydrothermal rock alteration, and in short shows all the features usually associated with vein formation.

[1] ECON. GEOL., 35: 698–736, 1940.

The second is near the Florence River in the Abitibi region of North Western Quebec. Here, there is an auriferous vein exposed on the surface for 850 feet. Quartz is conspicuously absent in surface exposures, its place being taken by a flesh colored feldspar which microscopic determination shows to be nearly pure albite (maximum extinction angle by the statistical method—19.5 degrees). The best values in this vein are always associated with albite. Underground, quartz is dominant in only one drift, and here the tenor of the ore is much lower than where albite is the predominant gangue mineral.

A point well taken by Mr. Gallagher in a foot note, is that the mineral sericite (usually determined by optical methods only) considered as indicating a potash content in the wall rocks may actually be its soda analogue, paragonite, and if the existence of the latter mineral can be proved by chemical analysis, in my opinion it practically clinches the proof in favor of the introduction of sodium into veins of the type described in the article.

The author in the first part of his paper makes the generalization that sodic feldspars in general characterize rocks in which the deposits carry gold as the only valuable metal, while in others in which silver or other metals are in considerable excess over gold, the genetically related igneous rocks are notably potassic.

My own impression with respect to these feldspars, is that their respective occurrence in connection with ore deposits is rather a function of conditions of formation than of the metal content of the veins themselves, in other words albite is characteristic of the mesothermal and hypothermal zones, and potash feldspar or adularia of the epithermal zone.

Adularia is a common mineral either in the veins or wall rocks in many epithermal gold veins, notably at Rawhide, Nevada, Gold Road, Arizona, Republic, Washington, Cripple Creek, Colorado, and Waihi, New Zealand.[2]

Albite on the other hand appears to be unknown in these deposits. Two gold mining districts which show considerable similarity in the metal content of their veins, but which were

[2] Lindgren, W.: Mineral Deposits, 1933, pp. 447 and 479.

formed under widely different conditions, are Cripple Creek and Kalgoorlie. In deposits of the former district, which are of epithermal origin, adularia is a prominent mineral, while albite is not reported, and in those of the latter (hypothermal according to Lindgren) albite occurs as an accessory vein mineral,[3] and potash feldspar appears to be absent.

In his reference to Kalgoorlie, Gallagher also specifies several authors mentioning albite in associated dikes and porphyries.

J. A. Reid.

85 Glendonwynne Rd.,
Toronto, Ontario,
Oct. 18, 1940.

[3] Op. cit., p. 680.

REVIEWS *

Strength and Structure of the Earth. By REGINALD ALDSWORTH DALY. Pp. ix, 434; Figs. 83; Tables 69. Prentice-Hall, New York, 1940. Price, $3.50.

This timely book performs two important services for students of tectonics. Primarily, it presents in brief and convenient form the most pertinent published data bearing on isostasy and the strength of the Earth's crust. The development of the idea of isostasy, geodetic evidence on which the concept is based, and geologic tests of the concept are the subjects to which the greater part of the book is devoted. Literature on these subjects, widely scattered and much of it difficult for the average student to evaluate, is concisely and clearly summarized in this new volume. Thus the factual aspect of the study receives the chief emphasis, and the book fills a long-felt need for a comprehensive treatise and an authoritative reference work in this large and difficult field.

But the subject of isostasy bristles with fundamental problems, and users of the book would not be satisfied without some attempt on the part of the author to interpret the evidence. This he does in his characteristically stimulating fashion. He suggests a "model Earth," with a strong lithospheric shell, 60 to 80 kilometers thick, resting on an asthenosphere which is nearly devoid of strength; probably it is composed of heavy rock, such as oceanite and peridotite, not crystalline but vitreous and potentially liquid. Regional data bearing on the strength of the lithosphere is somewhat conflicting, and it is suggested that this outer shell varies in thickness, the oceanic segments being thicker and stronger than average continental segments. Outstanding one-sign gravity anomalies in India, which Glennie has used as evidence opposed to isostasy, are shown to be a less formidable problem when reductions are made on the basis of Heiskanen's triaxial ellipsoid of 1938. In order to harmonize this assumed figure of reference with the concept of an asthenosphere devoid of strength at shallow depth, Daly assumes further that the asthenospheric shell has small thickness, and is underlain by a strong *mesospheric* shell, which extends to the central core. The assumed triaxial figure, with the

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

shorter equatorial axis about 704 meters less than the longer, is supposed to be maintained by the strong mesosphere. Daly recognizes that this concept is not consistent with the hypothesis of large-scale convection as a cause of crustal deformation; the two ideas are mutually exclusive, and must be considered as competing hypotheses.

We are indebted to Professor Daly for a highly useful study, involving much labor on his part and designed to make the way easier and more profitable for future students. Whatever may be the reactions to interpretations and hypotheses proposed by the author, the book has no rival as a comprehensive guide to a subject of increasing importance in geology.

CHESTER R. LONGWELL.

This Fascinating Oil Business. By MAX W. BALL. Pp. 445. Bobbs-Merrill Co., 1940. Price, $3.00.

It would be difficult to find anyone more competent to write this book. Versed in geology, exploration and technical, executive and consulting work in oil, the author brings a wealth of personal knowledge of this large and varied industry. It is a much needed book to inform the many who desire some knowledge of the petroleum industry without having to wade through technical detail and founder in its specialized vocabulary. To the uninitiated, delving into it is an entertaining voyage of discovery that explodes some popular misconceptions, does not overlook the romance of oil, and acquaints him with a lot of common sense facts about the industry in pithy language that everyone can understand. For example, the chapter on oil in the old world starts off as follows: "We Americans like to think we invented the earth, but if we claim the oil business as an American creation we are in error by at least 6000 years. . . . Perhaps you would enjoy a leisurely ramble about the world looking at its fields, ancient and modern."

The book tells what oil is, what the men do, how one picks the place and acquires the right to drill and how wells are drilled. It informs one of the principles and mechanics of producing, transporting, refining and selling the oil and it tells of the oil and resources of the various countries and the part it plays in this War. We readily excuse his misstatement that the Roumanian oil wells would be blown up if the country were occupied by Germany.

Everyone, student and layman alike, can profit from its reading, but particularly it is valuable for business men, manufacturers, bankers and investors who desire non-technical, factual information on this subject. Geologists can profit from the accurate and dependable information upon other phases of the industry and those within the industry can broaden their knowledge of activities outside of their own particular branch.

We heartily recommend it and congratulate Max Ball for his fine work and the service he has done us.

ALAN BATEMAN.

The American Empire. WM. H. HAAS, Editor. Pages ix + 407. Illus. Univ. of Chicago Press, Chicago, 1940. Cloth, 6 × 9. Price, $4.00.

In the foreword of this interesting and very readable book the editor reminds one that a democracy can survive only with a well informed citizenry. He also calls attention to the fact that the reading public in the United States is, "generally speaking, pathetically ignorant of the geographic background upon which the superstructure of the country is built." "Especially is there lacking an understanding of the problems confronting the outlying territories under the American flag." It is because of the need of this kind of information that the book has been offered by the editor and his eight collaborators. The subject matter of the text is presented from the standpoint of geography and the conclusions are formed on scientific data, based on the assumption that a nation's economic life rests on a physical background.

Each unit of the outlying territories of the United States is discussed in satisfactory detail, and in such a pleasing manner that the reader is kept interested in the subject from the beginning to the end of the volume. The history of each unit, the character of its people, its climate, its physiography, its resources, and its future economic and political prospects are all outlined in such an entertaining style that the book reads more like a story than like a text. It contains an enormous amount of information of a cultural value and a wealth of geographic and economic data. It is well worth reading by anyone who wishes to know more of conditions in the outlying portions of the United States, and particularly by one who contemplates a visit to any of them.

W. S. BAYLEY.

Principles of Human Geography, 5th Edit. By ELLSWORTH HUNTINGTON. Pp. 594. Wiley and Sons, New York, 1940. Price, $3.50.

This interesting book by a widely travelled author has been largely rewritten but it still emphasizes its concentration on human relationships and contains much new material and new illustrations. The nine parts deal with man's geographical relationship, and to the earth as a globe; fundamentals of climate, continents and oceans; man's relation to physiography, soil, minerals, and climate, regional relationships, and to man. It is interesting and instructive reading.

Prospecting for Gold. 7th Ed. By I. L. IDRIESS. Pp. 293. Illus. 23. Angus and Robertson, Ltd., Sydney, 1939. Price, 5 s.

The fact that this book is now in its seventh edition is evidence that it has been filling a demand for a simple account of satisfactory methods employed in the prospecting for gold. This edition differs from the third edition (THIS JOURNAL, Vol. 27 (1932), p. 400) mainly in the addition of a short chapter on prospecting for oil by W. G. Woolnough and a revision of the earlier text.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Mines of the Southern Mother Lode Region, Part II—Tuolumne and Mariposa Counties. C. E. JULIAN AND F. W. HORTON. Pp. 179; figs. 62. U. S. Bureau of Mines, Bull. 424. Washington, 1940. Price 60 cents. *Detailed account of the Mines in Tuolumne and Mariposa Counties; excellent photographs of ore specimens, and good cross sectional diagrams.*

Illinois Mineral Industry in 1939. W. H. VOSKUIL AND G. N. OLIVER. Pp. 52; figs. 9; tables 45. Ill. Geol. Surv., Report of Investigations No. 63. Urbana, 1940. *Statistics of Ill. mineral production in 1939, with special discussion of coal distribution in 1937.*

Oil and Gas Development in Illinois in 1939. A. H. BELL AND G. V. COHEE. Pp. 38; figs. 2; tables 7. Ill. Geol. Surv., Illinois Petroleum No. 35. Urbana, 1940. *Reprint, with additions, from "Recent Development and Technology," Trans. A. I. M. E., vol. 136, 1940. Pp. 268–80.*

Possibilities of Manganese Production at Leadville, Colo. J. H. HEDGES. Pp. 21; tables 5. U. S. Bureau of Mines, Inf. Cir., No. 7125. Washington, 1940.

Petroleum Statistics, 1935–38. G. R. HOPKINS. Pp. 61; tables 34. U. S. Bureau of Mines, Econ. Paper, No. 20, Washington, 1940.

Geology of the Chicago Region, Part I—General. J HARLEN BRETZ. Pp. 108; figs. 91; pls. 7; geol. map in color, 13″ × 27″, scale 1:125,000. Ill. Geol. Surv., Bull. 65. Urbana, 1939. *Non-technical paper, intended for use of schools and the layman.*

Characteristics of Minable Coals of West Virginia. A. J. HEADLEE AND J. P. NOLTING, JR. Pp. 272; figs. 112; pls. 18; tables 6; maps 2, 32″ × 40″, scale 1:500,000, and 16″ × 18″. West Vir. Geol. Surv., Vol. 13. Morgantown, 1940. Price $1.53. *In two parts: Part 1—physical characteristics of coal seams; Part 2—statistical study of coal analyses.*

The Phosphate Resources of Tennessee. R. W. SMITH AND G. I. WHITLATCH. Pp. 444; figs. 7; pls. 14; tables 13; maps 3, inc. two geol. maps, 14″ × 17″, scale 1:65,000, in color, and 27″ × 32″, scale 1:250,000. Tenn. Geol. Surv., Bull. 48. Nashville, 1940. Price $1.00. *Comprehensive treatise, covering all aspects of the deposits.*

Gold Mining and Gold Deposits in New Mexico. E. H. WELLS AND T. P. WOOTTON, rev. by T. P. WOOTTON. Pp. 24. New Mexico School of Mines, State Bureau of Mines and Mineral Resources, Cir. No. 5. Santa Fe, 1940.

Ocorrência de Cinábrio em D. Bosco, Minas Gerais. E. P. SCORZA. Pp. 16; 1 sketch map. Brazil Div. de Geol. e Min. Notas Prelim. No. 18. Rio de Janeiro, 1939. *Occurrence, paragenesis, and origin of some newly discovered cinnabar deposits.*

Lower Cretaceous and Jurassic Formations of Southern Arkansas and Their Oil and Gas Possibilities. R. W. IMLAY. Pp. 71; pls. 26; tables 17; 13 maps. Ark. Geol. Surv., Inf. Cir. 12. Little Rock, 1940. *Excellent structure sections.*

Geologic Maps of various parts of Canada on a scale of 1″ = ½ mile are being produced together with short papers on the geology of the areas. Canada Dept. Mines and Resources, Geol. Surv. Paper 40. Price $.10 for each area.

The following have been received.

No. 40–1 **Jumpingpound, Alberta.** G. S. HUME. Prelim. Map. Ottawa, 1940.

No. 40–2 **Wildcat Hills Map-Area, East Half, Alberta.** C. O. HAGE. Paper and Prelim. Map. Pp. 9; 1 table. Ottawa. 1940.

No. 40–3 **Michwacho Lake, Abitibi Territory, Quebec.** H. H. BEACH. Prelim. Map. Ottawa, 1940.

No. 40–4 **Mechamego Lake, Abitibi Territory, Quebec.** H. H. BEACH. Prelim. Map. Ottawa, 1940.

No. 40–5 **Fish Creek, Alberta.** G. S. Hume. Prelim. Map. Ottawa, 1940.

No. 40–6 **Bragg Creek, Alberta.** G. S. HUME AND H. H. BEACH. Prelim. Map. Ottawa, 1940.

No. 40–7 **Gordon Lake South, Northwest Territories.** J. F. HENDERSON. Prelim. Map. Ottawa, 1940.

No. 40–8 **The Structure and Oil Prospects of the Foothills of Alberta between Highwood and Bow Rivers.** G. S. HUME. Pp. 22; figs. 2, inc. several structure sections. Ottawa, 1940.

No. 40–9 **Gordon Lake, Northwest Territories.** J. F. HENDERSON. Prelim. Map. Ottawa, 1940.

No. 40–10 **Stony Rapids and Porcupine River Areas, Saskatchewan.** G. M. FURNIVAL. Paper and two maps. Pp. 10. Ottawa, 1940.

No. 40–11 **The Lloydminster Gas and Oil Area, Alberta and Saskatchewan.** G. S. HUME AND C. O. HAGE. Pp. 12; figs. 1; tables 2. Ottawa, 1940.

No. 40–12 **Zeballos Mining District and Vicinity, British Columbia.** M. F. BANCROFT. Pp. 35. Ottawa, 1940.

No. 40–13 **Wapiabi Creek, Alberta.** B. R. MACKAY. Prelim. Map. Ottawa, 1940.

No. 40–14 **Quyta Lake and Parts of Fishing Lake and Prosperous Lake Areas, Northwest Territories.** A. W. JOLLIFFE. Pp. 9. Ottawa, 1940.

College Geography, 2nd Edit. E. C. CASE AND D. R. BERGSMARK. Pp. 767; figs. 295. Wiley and Sons. New York, 1940. Price $4.00.

Largely rearranged; material expanded and brought up to date; many new maps and illustrations; a good elementary text.

Mines Magazine—5th Ann. Petroleum Edit. Pp. 87. Colo. School Mines. Denver, 1940. Price $1.00. *16 articles on petroleum technology and geology; illustrated.*

Sur le gisement d'or de La Bellière (Maine-et-Loire, France). P. SEVENSMA. Pp. 12; figs. 5. Archives des Sciences Physiques et Naturelles, Period 5, vol. 22. Geneva, 1940. *Description of the gold deposits and principal associations of La Bellière.*

Northern Miner, Annual Number. Pp. 152. Northern Miner Press. Toronto, 1940. *Yearly review of Canadian mining industry, with excellent summary of new developments in mining industry and resources. Good reference..*

Informe del Ministro de Minas y Petroleos al Congreso Nacional en sus Sesiones Ordinarias de 1940. Bogota, Rep. de Colombia, 1940. *Economic, technical, and scientific reports of the chiefs in charge of State depts. dealing with petroleum, mines, and metallurgy.*

Dictionary of Geologic Terms. C. M. RICE. Pp. 461. Edwards Bros. Ann Arbor, Mich., 1940. Price $6.00. *A carefully edited, complete dictionary of all known geologic terms of all branches of geology, excluding only stratigraphic terms and paleontologic genera and species; includes all minerals, rocks, and petrologic terms. Indispensable to all students of geology.*

Cyaniding for Gold. I. L. IDRIESS AND A. N. GRAHAM. Pp. 270; tables 3; several unnumbered figs. and photographs. Angus and Robertson Ltd. Sydney and London, 1939. Price 10/-. *A clear discussion in popular style for layman and miner.*

Geology and Mineral Resources of the Warrenton Quadrangle, Virginia. A. S. FURCRON. Pp. 94; pls. 18; 1 fig.; tables 3. Virginia Geol. Surv., Bull. 54. University, 1939. Geol. map in color, 13½" × 17¼", scale 1:62,500. *General geology; some building stones.*

Estudos sobré o tratamento de agua por coagulação. E. OROSCO, E. F. ROCHA, AND E. G. DE ANDRADE. Pp. 27; figs. 50. Inst. Nacional de Tech. Rio de Janeiro, 1939.

Canadian Mines Handbook, 1941. Pp. 232. Northern Miner Press. Toronto, 1941. Price, $1.00. *Lists 5760 mining companies and detailed statistics of 682 active mines with 5 year comparisons of output and earnings.*

Mineral Industry, 1939, Vol. 48. Edit. by G. A. ROUSH. Pp. 761. McGraw-Hill Co. New York, 1940. Price, $12.00. *The customary excellent volume brought up to date, and reflecting war conditions.*

SOCIETY OF ECONOMIC GEOLOGISTS

NEW YORK MEETING, 1941

The Society of Economic Geologists met in New York City on February 17–19 in conjunction with the Mining Geology section of the American Institute of Mining and Metallurgical Engineers. Thirty-eight papers were presented at six technical sessions—one session devoted to the influence of geophysics upon geology curricula, two to metalliferous deposits, one to ground water geology, one to strategic minerals, and one to non-metallic deposits. All six sessions were joint sessions with one or more of the technical committees of the Institute.

President G. F. Loughlin delivered an address on "Comments on the Origin and Structural Control of Mineral Deposits" at the annual dinner at the Mining Club on Tuesday evening, February 18. Following the dinner, the annual meeting was held, at which a brief report was made by the Treasurer, J. T. Singewald, Jr. The assets of the Society at the close of the fiscal year, November 30, 1940, were valued at $49,875.52.

Alan M. Bateman was installed as President, and W. J. Mead as Vice-President for 1941.

The following officers were elected in the letter ballot that closed January 1:

President for 1942.

W. J. Mead

First Vice-President for 1942.

K. C. Heald

Regional Vice-Presidents for 1941.

Ben Lightfoot,	For Africa
J. A. Dunn,	For Asia
H. J. C. Connolly,	For Australia
F. A. J. Blondel,	For Europe
Manuel Santillan,	For North America
Friedrich Ahlfeld,	For South America

Councilors for 1941–1943.

W. E. Pratt
D. G. Thompson
A. B. Yates

E. R. Lilley was appointed Councilor for the term ending in 1941, to succeed Philip Krieger.

The Council confirmed the election of the following new members:

J. W. H. Adam
F. F. Barnes
C. S. Blair
T. A. Dodge
N. H. Fisher
G. M. Furnival
J. O. Harder
F. T. Ingham
C. A. Lamey
Andrew Leith
W. W. Longley
B. C. Moneymaker
J. L. Rich
Jack Satterly
W. S. T. Smith
Manuel Tello B.
H. O. Amick
A. J. Blair
R. S. Cannon, Jr.
D. Le Count Evans
M. H. Frohrerg
D. L. Gardner
Harold Hopkins
T. L. Kesler
R. A. Laurence
S. W. Lohman
R. D. Longyear
T. G. Moore
Takao Sakamoto
A. N. Sayre
V. P. Sondhi
E. S. Willbourne

The following committees for 1941 have been appointed by the President and Council.

Executive Committee

Alan M. Bateman, *Chairman*
L. C. Snider
Wallace E. Pratt
D. H. McLaughlin
A. W. Pinger

Finance Committee

Arthur Notman, *Chairman*
S. H. Ball
W. J. Mead
Wallace E. Pratt

Program Committee

H. E. McKinstry, *Chairman*
D. G. Thompson
W. H. Newhouse

Penrose Gold Medal Committee

Adolph Knopf, *Chairman*
W. S. Butler
T. S. Lovering

SCIENTIFIC NOTES AND NEWS

EMMONS MEMORIAL FELLOWSHIP.

The Emmons Memorial Fellowship in Economic Geology is available for this year (stipend $1200). Applications and accompanying testimonials should be submitted not later than April 15th. Applicants should be qualified by training and experience to investigate some problem in economic geology and should submit a definite statement of the problem to the committee, under whose oversight the work will be undertaken at any institution approved by them. The Fellow must give his entire time to the problem which may be used for a doctorate dissertation. Application blanks and further information may be obtained from Alan M. Bateman, Charles P. Berkey, W. H. Newhouse, or the Secretary, Columbia University.

R. D. BUTLER, on leave from the geology department at Lehigh University, is doing geological work for the London Mine in Alma, Colorado.

The AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS will hold its twenty-sixth annual meeting at the Rice Hotel, Houston, Texas, April 2–4, 1941. The SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS will meet at the same time and place and the SOCIETY OF EXPLORATION GEOPHYSICISTS will meet in the same hotel April 1–3. Members of both these Societies are invited to attend the Association meetings and social activities.

A. L. RANSOME has been appointed assistant mineral economist for the U. S. Bureau of Mines in Washington.

P. F. KERR, associate professor of mineralogy at Columbia University, is in South America on a six months' lecture tour under the auspices of the Carnegie Endowment for International Peace.

R. L. FAULKNER, assistant geologist for Cerro de Pasco Corporation, has returned from Lima, Peru to Washington, D. C. where his address is 1426 21st St., N.W.

L. S. BRECKON, geologist for the Utah Copper Co. at Bingham Canyon, has been reelected president and managing director of the Rip Van Winkle Mining Co.

J. E. HAWLEY and N. W. BUERGER, of Queen's University, delivered papers on the synthesis of iron and nickel sulphides and controlled temperature x-ray technique, respectively, before the Walker Mineralogical Club of Toronto University on February 27.

F. R. DENTON and R. M. TROWBRIDGE, consulting geologists, announce the opening of offices in the Owen Building, Tyler, Texas.

JAMES HOPKINS is chief mining engineer for Luzon Stevedoring Company, which is producing manganese in two of the Philippine Islands.